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by

AXEL HOFMANN

(School of Geosciences, University of the Witwatersrand, Private Bag 3, P.O. Wits 2050, Johannesburg, South Africa

present address: School of Geological Sciences, Howard College Campus. University of KwaZulu-Natal, 4041 Durban, South Africa)

email: hofmann@ukzn.ac.za

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ABSTRACT

The 3500-3200 Ma old volcano-sedimentary succession of the Barberton greenstone belt, South Africa, is characterized by lithological units that are repeated in a regular manner. Ultramafic to dacitic volcanic and volcaniclastic sequences are typically capped by zones of silica enrichment, followed by beds of sedimentary cherts that are rich in carbonaceous matter. Cross-cutting carbonaceous chert dykes and veins are common in silica alteration zones and bedded cherts. A detailed field study of several chert horizons covering most of the stratigraphic succession of the Barberton belt revealed the importance of syndepositional hydrothermal activity for their origin. Bedded cherts consist of silicified sedimentary and tuffaceous material that was deposited on the seafloor. Silicification took place at the sediment-water interface, as a result of diffuse upflow of low-temperature hydrothermal fluids. This resulted in the formation of cap rocks impermeable for ascending hydrothermal fluids. Fluid overpressure resulted in the breaching of the cap rocks at times. Chert dykes contain angular host rock fragments, replace wall rocks, and show evidence of multiple dyke fillings and *in situ* brecciation of earlier generations of dyke fillings. They represent hydraulic fractures that were initiated by overpressuring of the hydrothermal system. The resulting vein networks, in both volcanic and sedimentary rocks, were then infilled, partly by hydrothermal chert precipitates, and partly by still unconsolidated sedimentary material derived from overlying sedimentary horizons. Most carbonaceous matter represents sedimentary material and did not form by hydrothermal processes, which supports a biogenic origin.

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INTRODUCTION

Chert is a minor, but important component of early Archaean greenstone belts of the Kaapvaal Craton in southern Africa and the Pilbara Craton in Western Australia. Chert, in the *c.* 3550 to 3220 Ma old Swaziland Supergroup of the Barberton greenstone belt (BGB) in South Africa, forms thinly bedded, stratiform horizons and consists of microcrystalline quartz with minor amounts of phyllosilicates, carbonate and oxide minerals, and carbonaceous matter (Lowe, 1999a; Walsh and Lowe, 1999). A distinct variety of black, commonly carbonaceous, chert forms cross-cutting veins that are present in particular stratigraphic units, and mostly beneath stratiform chert horizons.

Chert horizons have yielded important information on: (1) the (tectono-) stratigraphy of the BGB, because they represent good marker horizons (Viljoen and Viljoen, 1969a; Williams and Furnell, 1979; De Wit, 1982; Lowe and Byerly, 1999) and may contain volcanic or detrital zircons useful for dating purposes (Armstrong *et al.*, 1990; Kröner *et al.*, 1991; Byerly *et al.*, 1996, 2002); (2) the environment and tectonic setting of the volcano-sedimentary sequence, with sedimentary structures providing indicators of palaeo-water depth (Lowe and Knauth, 1977; Lanier and Lowe, 1982; Paris, 1990; Lowe, 1999a); and (3) the temperature and composition of the Archaean ocean, as deduced from evaporite pseudomorphs and ^{18}O signals (Lowe and Fisher Worrell, 1999; Knauth and Lowe, 1978, 2002). Most importantly perhaps, carbonaceous chert horizons in the BGB and greenstone belts of the Pilbara Craton contain the oldest morphological evidence for life on Earth in the form of microfossils (Awramik, 1983; Walsh, 1992; Westall *et al.*, 2001; Schopf, 2002), indicating that life evolved early in geological history. However, the oldest microfossil-like structures of putative biological origin from 3465 Ma cherts in greenstone belts of the Pilbara Craton have also been regarded as secondary artefacts (Brasier *et al.*, 2002). This reinterpretation is partly based on the presence of the microfossil-like structures in black chert dykes, interpreted to represent high-temperature (>250°C) hydrothermal veins rather than primary sedimentary chert. In addition, micron-sized filaments that are similar to filamentous microfossils have been synthesized inorganically (Garcia-Ruiz *et al.*, 2003), casting further doubt on the currently accepted evidence for life forms in ancient cherts. Similarly problematic are light carbon isotope signatures of ancient carbonaceous matter, which, although long been cited as evidence that life evolved probably as early as 4000 Ma ago (Schidlowski, 1988; Mojzsis *et al.*, 1996), may not record a biological signal (Horita and Berndt, 1999; Van Zuilen *et al.*, 2002). The same may be true for the light ^{13}C values obtained from early Archaean black cherts from the BGB and the Pilbara Craton (e.g., Oehler *et al.*, 1972; Hayes *et al.*, 1983; Walsh and Lowe, 1999; Ueno *et al.*, 2004). Better constraints on the origin of the carbonaceous matter in Archaean cherts is thus fundamental for an understanding of the early biological record. This study presents a summary of detailed field observations on the occurrence of carbonaceous cherts and their relationships with the host rocks at several stratigraphic levels of the BGB.

GEOLOGICAL SETTING

The BGB (Fig. 1) is one of the key areas for the study of mid-Archaean supracrustal sequences. The belt consists of a NE–SW striking, tightly folded succession of supracrustal rocks, termed the Swaziland Supergroup, and is surrounded by granitoid domes. The volcano-sedimentary sequence is subdivided into three stratigraphic units, the Onverwacht, Fig Tree and Moodies Groups. The Onverwacht Group formed between *c.* 3550 and 3300 Ma and consists of submarine ultramafic-mafic volcanic rocks and minor felsic volcanic and sedimentary rocks. South of the Inyoka Fault, the Onverwacht Group has been subdivided into six formations (Fig. 2), the Sandspruit, Theespruit, Komati, Hooggenoeg, Kromberg and Mendon (previously Swartkoppie) Formations (Viljoen and

Viljoen, 1969b; Lowe and Byerly, 1999). The Theespruit Formation is separated from the Komati Formation by the Komati Fault, whereas the overlying formations of the Onverwacht Group are, apart from local complexities, in stratigraphic continuity. Metamorphic grade is mainly greenschist facies, but locally reaches amphibolite facies close to intrusive plutons, in particular in the Sandspruit and Theespruit Formations. Onverwacht Group rocks north of the Inyoka Fault have been grouped together as the Weltevreden Formation (Lowe and Byerly, 1999). Differences in the stratigraphy, ages and depositional environments of rocks north and south of the Inyoka Fault suggests that the fault zone represents a tectono-stratigraphic boundary.

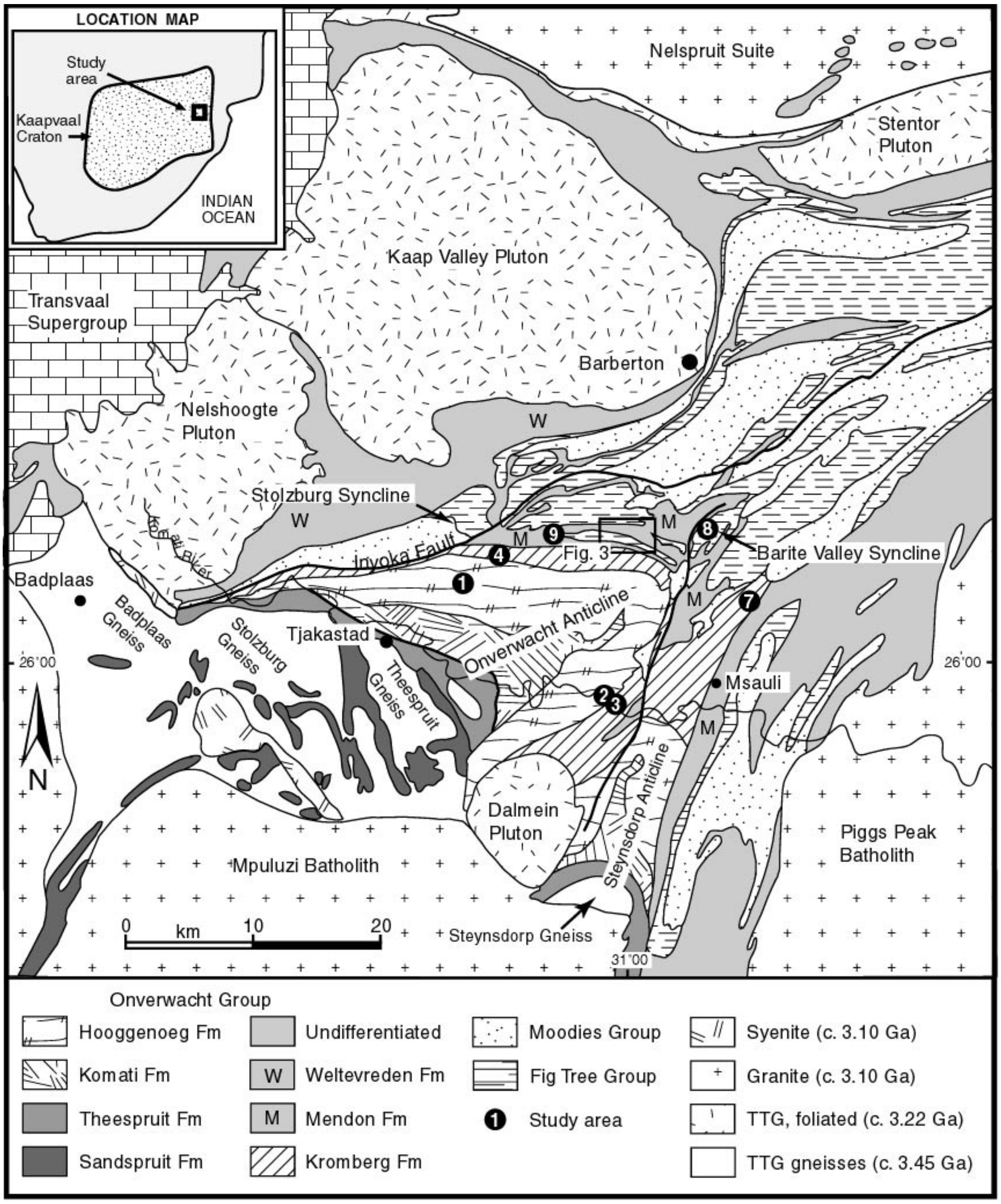

Figure 1. *Geological map of the western part of the Barberton greenstone belt (modified from Kamo and Davis, 1994; Lowe and Byerly, 1999).*

The Fig Tree Group, *c.* 3260-3226 Ma in age (Kröner *et al.*, 1991; Byerly *et al.*, 1996), comprises different facies associations in the northern and southern portions of the belt. The northern facies consists mainly of relatively deep-water turbiditic greywacke and shale with felsic volcaniclastic rocks at the top (Condie *et al.*, 1970; Eriksson, 1980; Lowe and Byerly, 1999; Kohler and

Anhaeusser, 2002). The southern facies is compositionally more variable and formed in a predominantly shallow-water setting. It includes a lower unit of shale, greywacke and jaspilitic banded iron formation, a middle unit of sandstone, shale and conglomerate with local detrital barite beds, and an upper unit of felsic volcaniclastic rocks (Heinrichs, 1980; Lowe and Nocita, 1999; Hofmann, 2005a). Two distinct sedimentary horizons (S2, S3) with spherules, interpreted to represent quenched liquid silicate droplets of meteorite impact origin (Lowe *et al*., 2003), occur at the base of both the northern and southern Fig Tree facies and in the middle part of the southern facies.

The Moodies Group was deposited at *c.* 3226 Ma ago (Kamo and Davis, 1994) and consists of shallow-marine to fluvial sandstone and conglomerate with minor shale and banded iron formation. The succession comprises relatively quartz-rich, predominantly arenaceous rocks in contrast to the more quartz-poor Fig Tree sandstones. The Moodies Group is *c.* 3 km thick and has been subdivided by Anhaeusser (1976) into three formations, each of which is a fining-upward sequence, ranging from conglomerates or pebbly sandstones at the base, to a thick sandstone unit, to capping siltstones and shales.

The BGB was intruded by a variety of granitoids during several magmatic episodes. The granitoids, with an age range from *c.* 3500 to 3200 Ma (Kamo and Davis, 1994), belong to the tonalite, trondhjemite, granodiorite (TTG) suite and have a prominent gneissic fabric, whereas the younger, *c.* 3100 Ma granitoids, are potassium-rich and form prominent sheets of granodiorite and monzogranite. Pre-Onverwacht Group tonalitic to granitic gneisses (Ancient Gneiss Complex) occur southeast of the greenstone belt in Swaziland and have been dated at *c.* 3644 Ma (Compston and Kröner, 1988).

CHERTS OF THE BARBERTON GREENSTONE BELT - TERMINOLOGY AND REVIEW

Field Distribution

Based on the spatial relationship with the country rock, two distinct chert units can be distinguished: (1) stratiform horizons; and (2) veins that cut across stratification, the latter termed chert dykes. Stratiform chert horizons are typically 1-20 m thick, except for the Buck Reef Chert (Fig. 2), which reaches a thicknesses of a few hundred metres (Viljoen and Viljoen, 1969b; Lowe and Byerly, 1999). With the exception of the Sandspruit and Komati Formations and to a lesser extent the Theespruit Formation, stratiform cherts are common throughout the Onverwacht Group and the lower part of the Fig Tree Group, but are rare to absent in the upper Fig Tree and Moodies Groups. Chert horizons frequently overlie ultramafic, mafic, and dacitic volcanic rocks that are intensely silicified in the uppermost few tens of metres (De Wit *et al*., 1982; Paris *et al*., 1985; Lowe and Byerly, 1986; Duchac and Hanor, 1987; Hanor and Duchac, 1990; Hofmann, 2005b).

Chert dykes are 0.1 to 3 m wide, up to a few hundred metres in length, and cross-cut the country rock mostly perpendicular to stratification. They are volumetrically much less important than stratiform chert horizons. Chert dykes are restricted to the Onverwacht Group and occur most commonly beneath stratiform chert horizons. Anastomosing chert veins that are oriented subparallel to stratification are commonly associated with the dykes. Chert dykes in the Barberton belt have never been the subject of a detailed study, and much of the present work is aimed at understanding the origin of these features.

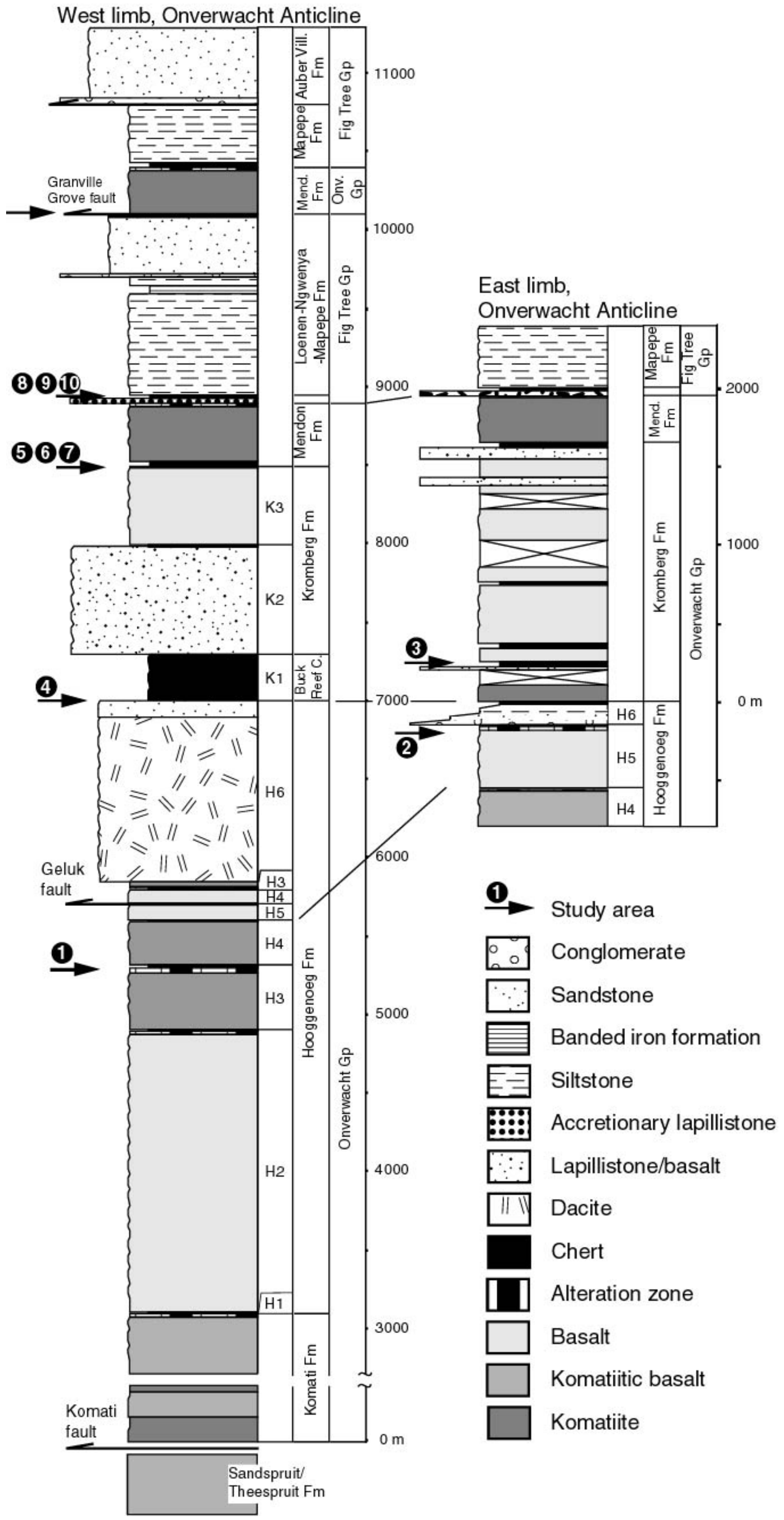

Figure 2. *Stratigraphic logs of the Barberton greenstone belt from the western and eastern limbs of the Onverwacht Anticline (modified from Lowe and Byerly, 1999).*

Composition

The petrography of stratiform chert horizons of the BGB has recently been summarized by Lowe (1999a). The cherts consist of microcrystalline quartz with minor, but varying amounts of phyllosilicates (sericite, chlorite), carbonates (calcite, dolomite, siderite), iron oxides, and carbonaceous matter. SiO_2 contents mostly exceed 90 wt. %. The cherts range in colour from green to grey to black; green colours are attributed to finely dispersed chlorite and Cr-rich sericitic mica (herein regarded as fuchsite), whereas dark grey to black coloration is attributed to the presence of carbonaceous matter. Red jaspilitic cherts also occur, but they are mainly associated with ferruginous shales of the Fig Tree Group.

Of particular importance for the purpose of this study are black cherts rich in carbonaceous matter. The carbonaceous matter occurs in four main petrographic varieties including fine laminations, irregularly-shaped simple grains, lobate clumps or composite grains, and wisps that are interpreted to represent compacted carbonaceous grains (Walsh and Lowe, 1999). Carbonaceous cherts include thinly bedded heterolithic rocks (black and white banded cherts), and laminated and massive black chert varieties. Black and white banded cherts are made up of layers of carbonaceous chert and white-weathering translucent chert.

Origin

Stratiform chert horizons consist of a variety of silicified sediments (Lowe and Knauth, 1977; Lanier and Lowe, 1982; Heinrichs, 1984; Paris, 1990; Lowe, 1999a; Lowe and Fisher Worrell, 1999). Four main groups have been identified by Lowe (1999a): (1) volcaniclastic and pyroclastic deposits; (2) terrigenous sediments; (3) biogenic sediments; and (4) orthochemical deposits. The first group includes silicified beds of komatiitic ash and accretionary lapilli that commonly overlie komatiitic volcanic sequences and are typically represented by light-green to greenish-grey cherts. Silicified dacitic volcaniclastic sediments occur at the top of the Hooggenoeg Formation and at the base of the Fig Tree Group, whereas basaltic, sediment-derived cherts are less common or less easy to distinguish. The latter chert types contain admixed carbonaceous matter and are typically well laminated cherts of various shades of grey. Silicified terrigenous sediments include black cherts derived from sandstone and siltstone in the lower Fig Tree Group and possibly from carbonaceous shales in the Onverwacht Group. Massive to laminated black cherts and black and white banded cherts have been regarded as silicified biogenic sediments by Lowe (1999a). They are common throughout the Onverwacht Group with banded cherts being particularly well developed in the Buck Reef Chert. Silicified orthochemical deposits include rare silicified evaporites, possibly primary sea-floor silica deposits in the form of translucent cherts, and banded iron formation and associated ferruginous rocks. Silicified volcanic rocks are also common, especially in alteration zones beneath chert horizons (Duchac and Hanor, 1987; Hofmann, 2005b), and are a distinct group altogether.

Silicification

According to Lowe (1999a), silicification of many sedimentary chert horizons (shallow-water deposits in particular) took place very early in the depositional history. This is indicated, for example, by the preservation of a high primary porosity (now infilled by chert) in coarse-grained clastic and tuffaceous deposits, the absence of compaction features, and the presence of chert clasts in intraformational breccias and conglomerates. Controversy surrounds the cause of silicification. Some authors associate silicification with convective circulation of hydrothermal fluids, resulting in subsurface metasomatism and/or deposition of silicious exhalites around hydrothermal vents (De Wit *et al.*, 1982; Paris *et al.*, 1985; Duchac and Hanor, 1987). Lowe (1999a), on the other hand, suggested that much of the silicification took place during interaction between sea water and sediments close to the sediment-water interface, as indicated, for example, by evidence for very early silicification over wide areas and the absence of more typical exhalative deposits, such as sinter or massive sulphide deposits. Hofmann (2005b) presented evidence for silicification of sea floor sediments and underlying volcanic rocks by low-temperature hydrothermal activity as a result of high regional heat flow.

Palaeontological Significance

A variety of spherical, rod-shaped and filamentous microscopic features that consist of carbonaceous matter have been recorded from Onverwacht and Fig Tree Group cherts and interpreted as microfossils in numerous early studies (references in Schopf and Walter, 1983). A re-evaluation of the purported microfossils by Schopf and Walter (1983) led to the conclusion that only a few features could be regarded as being of possible biogenic origin, whereas others were regarded as nonfossils, including pseudofossils, artifacts of sample preparation, and modern contaminants. More recent reports of filamentous microfossils and traces of bacterial activity in carbonaceous cherts include studies by Walsh and Lowe (1985), Walsh (1992), Westall *et al*. (2001), and Tice and Lowe (2004). These studies focused on carbonaceous cherts of the uppermost Hooggenoeg and Kromberg Formations.

CHERTS OF THE BARBERTON GREENSTONE BELT

Stratiform chert horizons and chert dykes have been investigated at several stratigraphic levels in many different parts of the greenstone belt, from the Hooggenoeg Formation to the Fig Tree Group (Figs. 1, 2). Cherts at the top of the Onverwacht Group and those associated with the Fig Tree Group have been investigated mainly in the central part of the greenstone belt (Fig. 3), herein referred to as the central study area.

Carbonaceous cherts are generally dark grey to black, and fresh rock splinters are opaque. On the other hand, black cherts are not necessarily carbonaceous, especially black cherts that, when fresh, are translucent to some degree. Translucent cherts commonly show botryoidal features. In the following account the term carbonaceous will be used for cherts where carbonaceous matter has been identified in thin section. Terms like opaque and translucent will be used for black cherts that were only studied in the field.

Hooggenoeg Formation

The Hooggenoeg Formation (Fig. 2) overlies the Middle Marker chert, dated at 3472±5 Ma (Armstrong *et al.*, 1990), and consists of massive and pillow basalt, spinifex-textured komatiitic basalt, thin silicified sedimentary horizons, and, at the top of the sequence, intrusive dacitic volcanic rocks and an epiclastic sedimentary unit. The dacitic rocks have been dated at *c.* 3445 Ma (Armstrong *et al.*, 1990). Lowe and Byerly (1999) subdivided the succession into several stratigraphic units (H2-H5), each of which is represented by a volcanic interval (H2v-H5v) that is capped by a 1-15 m thick chert horizon (H2c-H5c). The Middle Marker is regarded as H1 and the dacitic volcanic and volcaniclastic rocks are denoted as H6. Each chert horizon is underlain by a metasomatic alteration zone that is characterized by silicification, the presence of Cr-bearing sericite, stratiform chert, quartz and carbonate veins, and, locally, chert dykes.

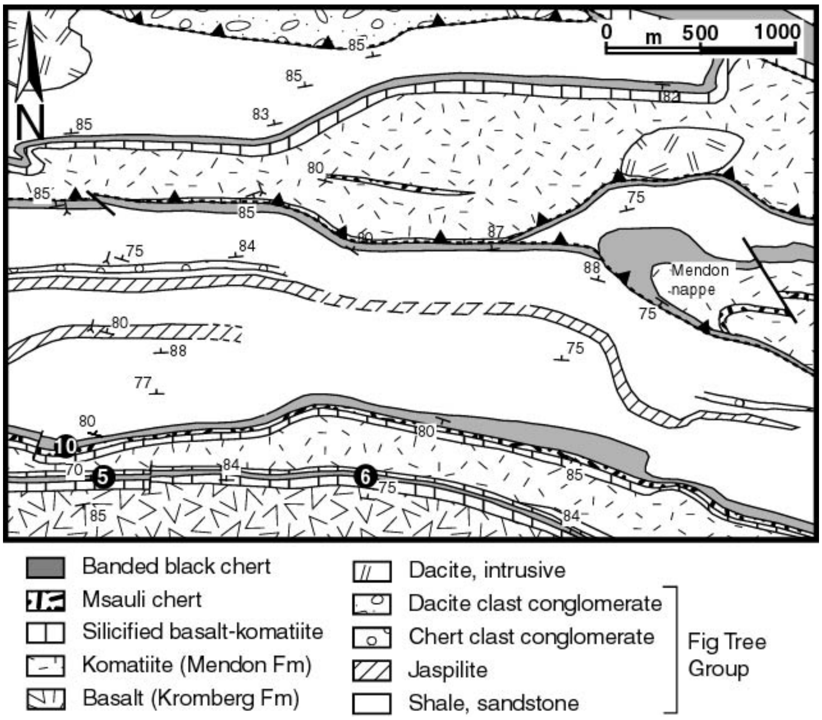

Figure 3. *Geological map of an area in the central part of the Barberton greenstone belt, termed the central study area (see Fig. 1 for location). Note the tectonic duplication of the Mendon Formation and overlying Fig Tree Group. Sedimentary rocks below, and volcanic rocks above, the thrust fault are altered to black chert.*

Hooggenoeg Formation - H3c

<u>Description:</u> A 10-15 m thick and laterally continuous chert horizon (H3c of Lowe and Byerly, 1999) occurs in the middle part of the Hooggenoeg Formation (Fig. 2). In the study area (Fig. 1, locality 1), the chert is underlain by pillow basalt, which is silicified in the uppermost 30 m. Silicification increases towards the basalt-chert contact. Anastomosing veins of carbonaceous chert, up to 8 cm wide and oriented subparallel to the stratification, occur in the uppermost 2.5 m of the basalt sequence and increase in frequency upsection (Fig. 4a). Some veins grade laterally from massive carbonaceous chert into botryoidal black and white chert with internal quartz mineralization.

The contact between basalt and bedded chert is sharp and planar. The chert horizon commences with a laminated carbonaceous chert that locally contains a bed of fine basalt pebble conglomerate. A thin basalt flow also occurs near the base, but is sheared out locally. Black chert is overlain by stratified, but otherwise massive, greenish-grey chert, followed by unstratified greenish-grey chert that contains cm-scale translucent chert veinlets. Apart from crude layering, no sedimentary structures are present. Massive chert is succeeded by stratified greenish-grey chert, followed by interbedded greenish-grey and black carbonaceous chert. Soft-sediment deformation features are common in the latter unit, as indicated by common load structures of grey chert into black chert and sediment convolution (Fig. 5a). A second carbonaceous chert variety forms massive, mostly bedding-parallel veins, up to 15 cm wide, in the uppermost two chert units (Fig. 4a). The veins cross-cut, and contain fragments of, the host rock (Fig. 5b). The chert horizon is overlain by poorly exposed, massive, but not silicified mafic volcanic rocks.

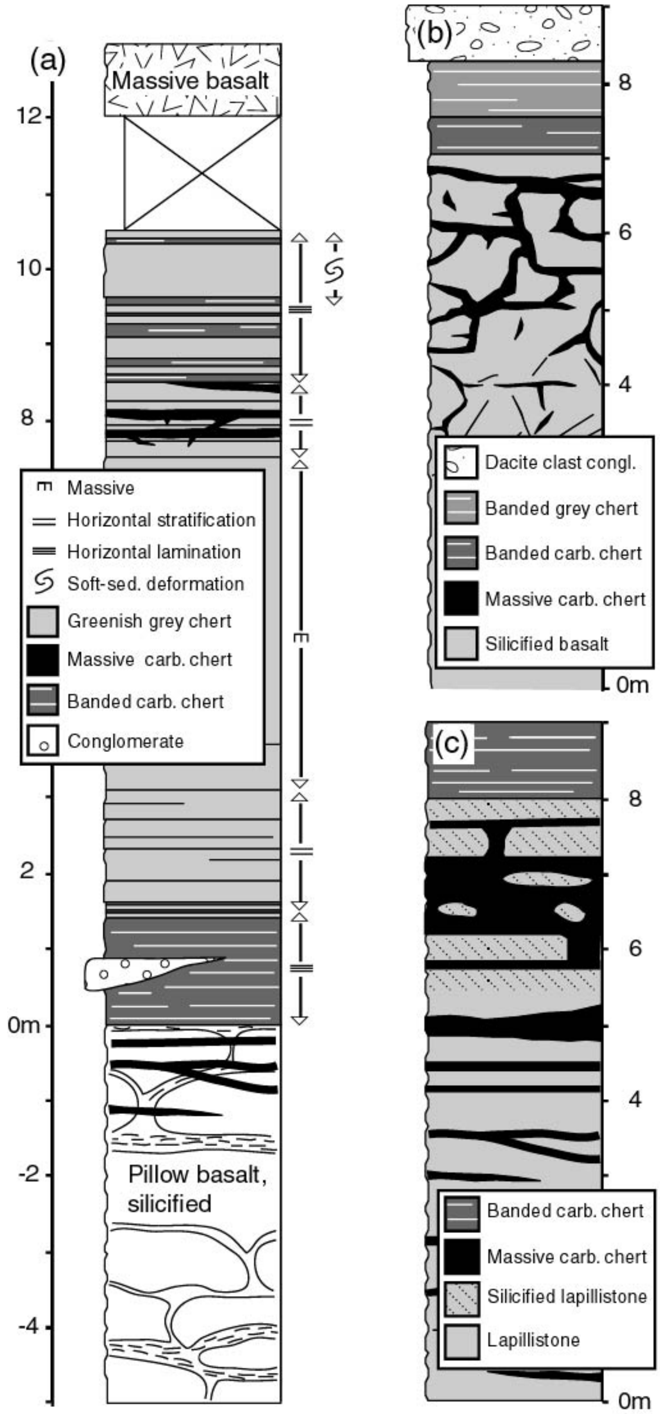

Figure 4. *Simplified measured sections of (a) chert horizon H3c of the Hooggenoeg Formation, (b) chert horizon H5c of the Hooggenoeg Formation, and (c) a section exposed beneath chert horizon K1c1 of the Kromberg Formation.*

Both bedded and cross-cutting black cherts contain carbonaceous matter, mostly in the form of equant to elongate, but also disrupted, irregular grains that range from silt size up to 1 mm in diameter and are typically 200µm across. Grains in the lowermost bedded chert, and in veins cutting basalt, are loosely packed (Fig. 6a), whereas grains in sedimentary and vein chert near the top have been somewhat flattened as a result of compaction (Fig. 6b). Cross-cutting cherts contain sand-sized grains that are replaced by chert or phyllosilicates, some of which are enveloped by carbonaceous matter. Idiomorphic sulphide grains, 50-200µm in diameter, are common and are, in places, associated with cross-cutting chert veinlets.

Interpretation: Chert horizon H3c consists of mainly two varieties of silicified sediments. Greenish-grey chert represents subaquatically deposited and reworked, silicified tuff beds of komatiitic basalt composition (Hofmann, unpubl. data). Laminated black chert probably represents background suspension sediments that were laid down during intervals of volcanic quiescence. Detailed sections of H3c were reported by Lowe (1999a), who regarded the rocks as having formed in a shallow subtidal setting. In contrast, veins of massive black chert are not directly part of the sedimentary sequence. The veins can neither be regarded as simple fissures that were filled by carbonaceous sedimentary material, nor as feeder channels for the sedimentary black cherts, as indicated by their stratiform geometry as well as cross-cutting relationships with banded cherts. Many veins contain angular host rock fragments and show hydraulic fracture patterns (*cf*. Laznicka, 1988; Jebrak, 1997), suggesting that they were initiated by the forceful intrusion of overpressured fluids. The presence of botryoidal chert and megaquartz in veins along the basalt-chert contact is consistent with a hydrothermal origin of the fluids. On the other hand, all chert types are petrographically very similar, because they contain sand-sized carbonaceous grains of apparent detrital origin. Because carbonaceous chert with plastic deformation features occurs in the sequence, some vein chert (especially that near the top of the sequence) may have been derived from sedimentary chert by dewatering and squeezing out of gelatinous silica during compaction. That the chert became lithified relatively late is attested by some compaction of the carbonaceous matter. A small-scale hydrothermal system that was initially open to the sediment-water interface, but became closed during progressive sedimentation and silicification, resulting in the buildup of fluid overpressure and hydraulic fracturing, may have resulted in the formation of similar features, like the veins that occur at the base of the section.

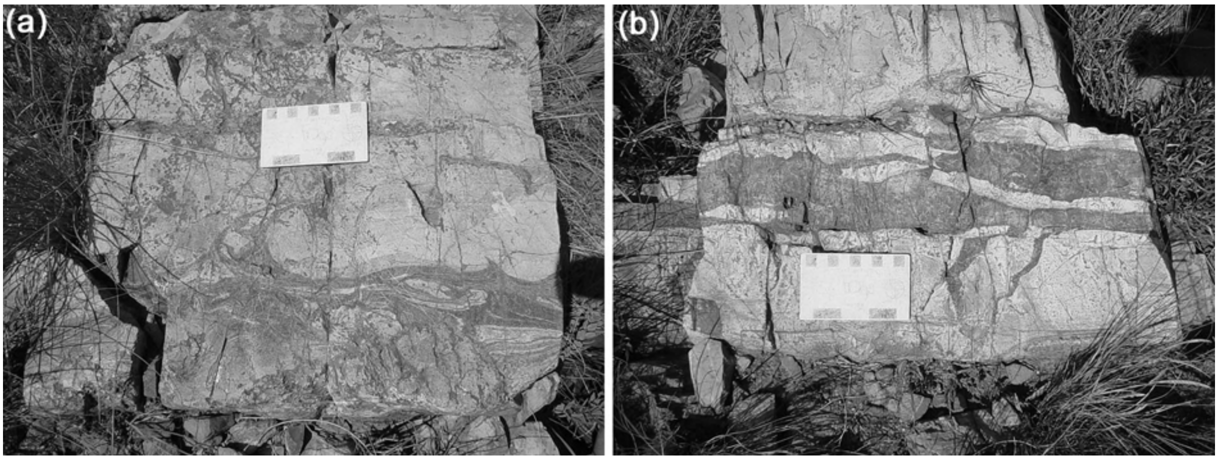

Figure 5. *(a) Load and flame structures at the base of a grey chert bed overlying black chert. Bedding in black chert is strongly convoluted. (b) Stratiform black chert vein transecting stratified grey chert. Note the fracturing of host rock by chert veins.*

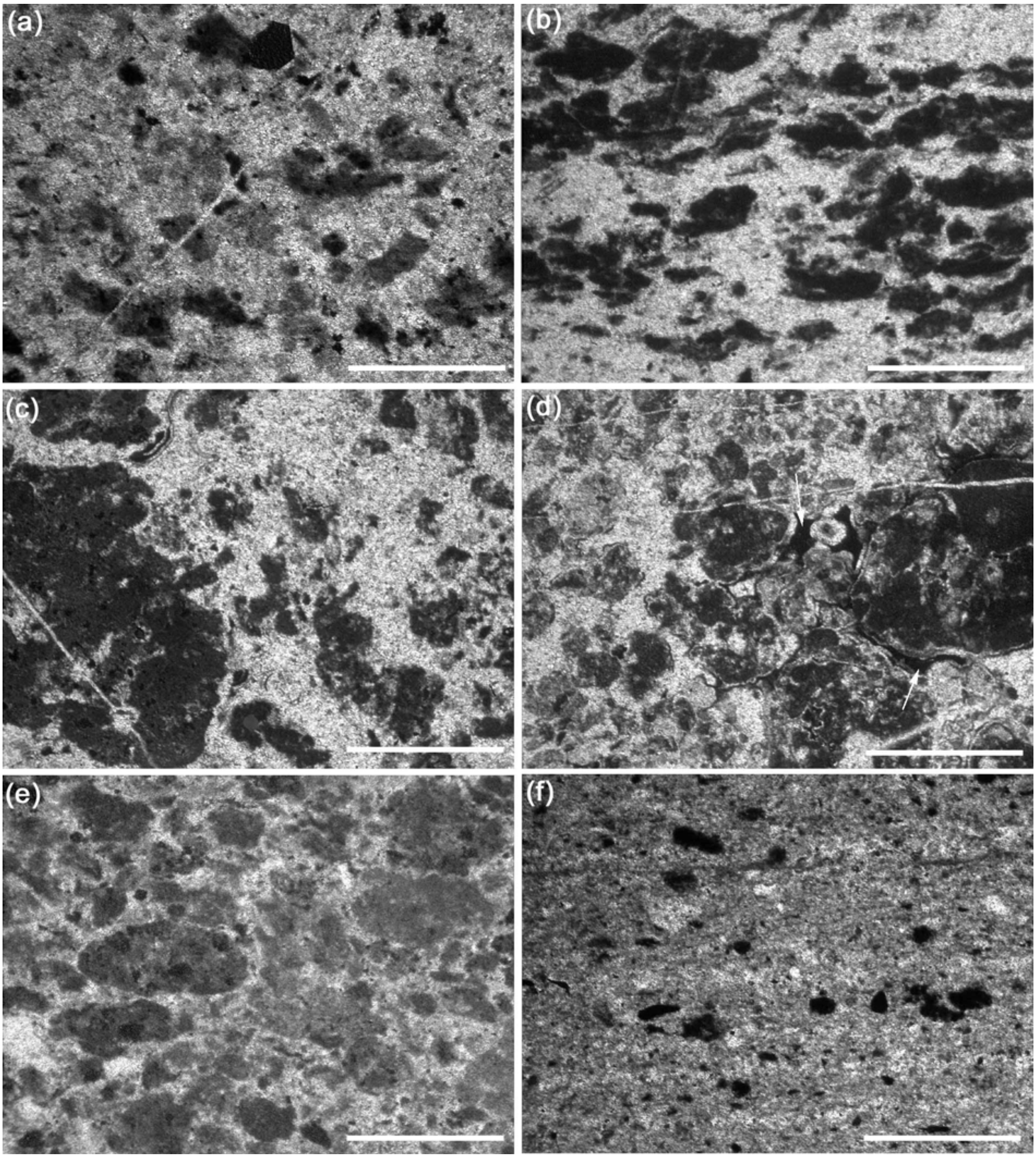

Figure 6. *Photomicrographs of carbonaceous sedimentary cherts and chert dykes; plane polarized light, scale bars are 500 µm long. (a) Carbonaceous grains in chert dyke below chert horizon H3c. Note idiomorphic sulphide grain (top centre). (b) Flattened carbonaceous grains near the top of H3c. (a) Loosly packed disrupted fragments of carbonaceous chert in a chert dyke below H5c. (d) Single and composite carbonaceous grains in sedimentary chert K1c1. Note botryoidal cements that enclose carbonaceous material (arrows). (e) Ellipsoidal carbonaceous grains filling a chert dyke below the Buck Reef Chert. (f) Silicified siltstone containing disseminated carbonaceous grains.*

Hooggenoeg Formation - H5c

Description: A few hundred metres thick sequence of pillow basalt and minor massive basalt forms the uppermost part of the Hooggenoeg Formation on the east limb of the Onverwacht Anticline (Fig. 2). The basalt sequence is capped by a thin chert horizon (H5c of Lowe and Byerly, 1999) that has been studied at one locality (Fig. 1, locality 2). Starting from *c.* 50 m below the chert bed, pillow basalt becomes silicified upsection and is transected by a network of massive carbonaceous chert veins in the uppermost 5 m (Fig. 4b). The veins have a random orientation and become more common and wider (5-25 cm) upsection, resulting in an equal chert- to host-rock ratio near the top (Fig. 7a). The dykes surround, rather than contain, angular basalt fragments, and some dykes consist of several generations of dyke material. Rare irregular contacts between chert and host rock indicate minor host-rock replacement (Fig. 7b).

Chert-veined basalt is capped by a *c.* 1 m-thick horizon of massive to thinly laminated black carbonaceous chert. Black chert is overlain by laminated grey chert, which contains some normally graded laminae with accretionary lapilli. Where the basalt-chert contact is exposed, chert sharply overlies silicified basalt that contains abundant translucent chert veins and patches; black chert forms stratiform veins 10 cm below the contact. Rare bedding-parallel veins of botryoidal black and white chert are present in the chert horizon, indicating that it too was affected by chert veining. The chert horizon is overlain along a sharp and planar contact by a dacite cobble conglomerate that forms the base of a *c.* 170 m-thick, upward-fining sedimentary sequence (Viljoen and Viljoen, 1969a). Cross-cutting veins of botryoidal chert are rare.

Sedimentary black chert consists predominantly of equant, sand-sized, carbonaceous grains. Chert dykes consist of different domains. One domain consists of tightly packed, equant, sand-sized, carbonaceous grains similar to the sedimentary chert. Later, cross-cutting material consists of loosely packed, irregular fragments of the latter (Fig. 6c).

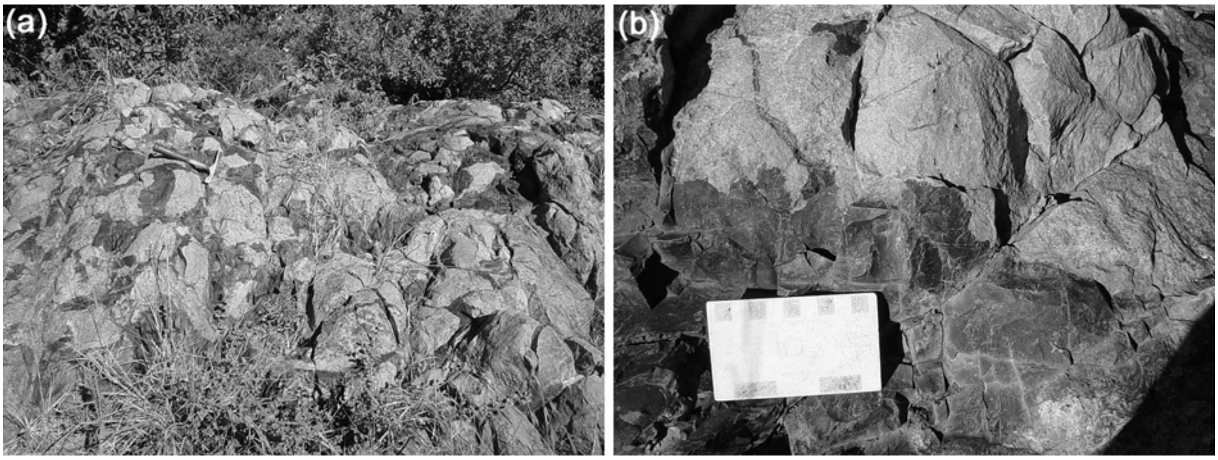

Figure 7. *(a) Network of black chert veins cross-cutting silicified basalt 2-3 m below the basalt-chert contact. (b) Irregular, finger-like protrusions of black chert replacing silicified basalt.*

<u>*Interpretation:*</u> Chert horizon H5c is compositionally similar to H3c. Greenish-grey chert represents silicified basaltic to komatiitic tuff beds, as indicated by the presence of accretionary lapilli and trace element contents (Hofmann, unpubl. data), whereas laminated black chert represents background suspension sediments that include possible biogenic material. Filamentous microfossils have been reported from this horizon to the north of the study locality (Walsh and Lowe, 1985; Walsh, 1992). The planar contact between chert and conglomerate indicates lithification of the chert bed prior to deposition of the conglomerate. This relationship is also indicated by the presence of rare black and grey chert clasts in the conglomerate, suggesting local erosion of the chert bed.

Black chert veins transecting basalt beneath the chert horizon are interpreted to be of hydrothermal origin. This is indicated by the geometry of the fracture pattern and wall rock replacement. On the other hand, the compositions of both chert varieties are similar. Both contain carbonaceous grains, suggesting a genetic link between dykes and sedimentary horizons. However, chert dykes also exhibit a high proportion of internal cross-cutting veins that contain fragments of carbonaceous chert, thus reflecting a multistage development.

Diffuse upflow of hydrothermal fluids is envisaged during deposition of the sedimentary chert precursor. This system became closed during progressive sedimentation and hydrothermal sediment silicification. The sedimentary chert horizon acted as a poorly permeable barrier for ascending fluids, resulting in fluid overpressure and hydraulic fracturing of the basalt. The fractures were filled with detrital material from the overlying sediments for some time before the hydraulic system was sealed again and the next cycle of pressure buildup and fracturing took place. Rare botryoidal chert veins cutting overlying conglomerate suggest that the hydrothermal system was active well after deposition and lithification of the conglomerate unit. Alternatively, these chert veins are part of a much later hydrothermal event.

Kromberg Formation - K1c1

Description: A banded chert horizon near the base of the Kromberg Formation (Fig. 2), termed K1c1 and correlated with the Buck Reef Chert by Lowe and Byerly (1999), crops out along the Komati River (Fig. 1, locality 3). The exposed section starts with a fuchsite-chert-carbonate alteration zone that is overlain by carbonated, stratified lapillistone. Stratiform botryoidal and massive black chert veins less than 5 cm thick are common in both units. In the upper part of the section, stratiform black chert veins become more numerous, resulting in massive black chert that contains matrix-supported lapillistone fragments near the top (Fig. 4c). Lapillistone becomes progressively more silicified upsection. This is followed by a several metres thick chert horizon (K1c1) that consists of black and white banded chert.

Both vein and sedimentary black cherts contain carbonaceous material in the form of sand-sized grains. Botryoidal chert cement is common and is frequently interlayered with, or encloses, carbonaceous material of a different generation (Fig. 6d).

Interpretation: Chert vein geometry at the top of the volcaniclastic sequence suggests a hydrothermal origin of the veins. The increase in veining upsection suggests some ponding of hydrothermal fluids below chert at times. Lapillistone becomes more silicified towards the top, suggesting that silicification and chert veining were contemporaneous. The same hydrothermal processes as discussed for H5 are envisaged to explain the field relationships.

Buck Reef Chert (BRC)

Description: In the study area on the west limb of the Onverwacht Anticline (Fig. 1, locality 4), the BRC has been subdivided into three facies (Lowe and Fisher Worrell, 1999; Lowe and Byerly, 2003; Tice and Lowe, 2004): (1) a basal evaporitic facies, containing volcaniclastic sedimentary rocks, chert and silicified evaporites; (2) a middle platform facies of black and white banded chert; and (3) an upper basin facies of banded ferruginous chert (Fig. 8). A variety of fossil-like microstructures have been reported from the BRC (Walsh, 1992).

The BRC overlies a dacitic igneous body, up to 2 km thick, termed member H6 of the Hooggenoeg Formation and interpreted as a large intrusive to extrusive lava dome and associated volcaniclastic sedimentary rocks (Lowe and Byerly, 1999; Lowe *et al*., 1999). The contact between H6 and the BRC is gradational. Massive, silicified dacite grades into conglomerate, pebbly sandstone, and massive to planar bedded, coarse-grained sandstone. The clasts consist entirely of dacitic volcanic rock, except for rare chert clasts. The sedimentary rocks are strongly silicified and detrital grains are variably replaced by chert. Parallel- and ripple-laminated chert is interbedded with, and overlies, silicified sandstone. The chert consists of interbedded translucent chert and black carbonaceous chert, and is frequently transected by elongate crystal pseudomorphs. Lowe and Fisher Worrell (1999) provided a detailed description of the facies preserved along the H6-BRC contact, which were interpreted to have formed in a coastal braid plain-sandflat setting. Replaced crystals were interpreted to represent pseudomorphs after nahcolite.

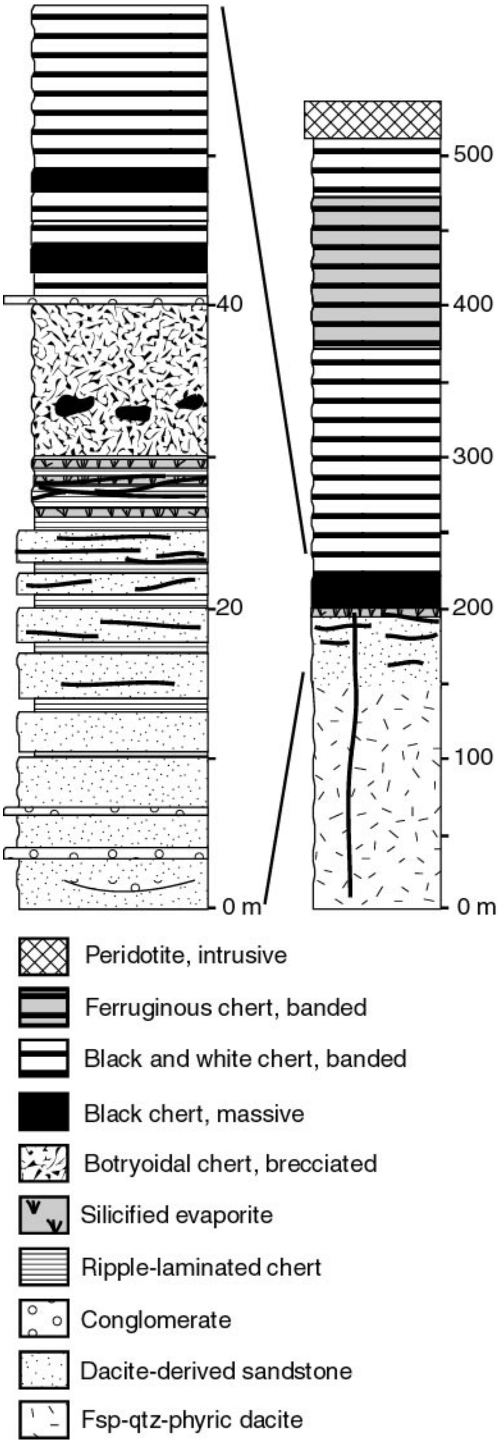

Figure 8. *Simplified section of the Buck Reef Chert.*

The silicified sandstone facies is overlain along a sharp contact by cherts that mostly lack sandstone interbeds. In the lowermost unit occur ≤ 0.5 m thick layers of silicified evaporites that are overlain by chert-clast breccias, with fragments of banded and evaporitic chert in a botryoidal chert and quartz matrix. The centres of some botryoidal chert and quartz fillings contain massive carbonaceous chert. Lowe and Fisher Worrell (1999) interpreted the chert breccias as evaporite dissolution cavities that were filled by botryoidal chert under mostly phreatic zone conditions. Carbonaceous chert in cavities was regarded as an injection of carbonaceous ooze, arresting complete precipitative filling. The evaporitic and botryoidal cherts are locally overlain by thin units of chert-clast conglomerate, black carbonaceous chert and green chert (Lowe and Fisher Worrell, 1999), and are succeeded by banded cherts of the shallow to deeper water platform and basin facies (Tice and Lowe, 2004).

Thin, randomly oriented veins of translucent chert (0.5 to 1 cm, but rarely up to 5 cm wide), are common in the uppermost few hundred metres of the dacitic unit. Farther upsection, stratiform chert veins, 1–30 cm wide, are very common in the conglomerate and sandstone facies at the H6–BRC contact. The veins consist of massive carbonaceous as well as botryoidal chert; some massive black chert veins grade laterally into botryoidal chert. The chert veins transect the host rock subparallel to bedding and partly brecciate it (Fig. 9a). Many horizons, up to 50 cm wide, are superficially similar to banded sedimentary chert, but, instead, consist of multiple stratiform veins, as indicated by the presence of angular fragments of chert and dacitic host rock (Fig. 9b). Furthermore, botryoidal chert veins, up to 50 cm wide, are present that are similar to the evaporite dissolution cavities at the base of the BRC. Most contacts between chert and host rock, including host-rock fragments, are sharp. In rare cases, however, does botryoidal chert replace the host rock. Furthermore, the matrix of some conglomerate beds is intruded and/or replaced by botryoidal chert. Chert veining is most intense immediately below the evaporitic and botryoidal chert unit. Rare chert veins also occur within this unit, whereas chert veins were not observed in the banded chert unit above, although identification is obscured because of the compositional similarity.

Several chert dykes that are oriented at a high angle to stratification (60-90°) transect the dacitic volcanic and sedimentary rocks of H6. The larger ones start at least 250 m below the BRC and appear to taper downward. They do not transect the silicified evaporite and associated breccia horizon at the base of the BRC. The dykes are ≤ 2 m in width. They show a crude internal layering parallel to the dyke walls (Fig. 9c), because they are made up of multiple generations of dyke fills as well as small cracks and veins, including botryoidal chert veins. Dykes, when fresh, consist of massive black chert; weathered surfaces reveal a fragmental, granular fabric caused by the presence of sand- to fine pebble-sized, angular clasts of white-weathering, probably host-rock material. Some "dykes in dykes" contain angular black chert fragments of the dyke host rock (Fig. 9c). Wherever cross-cutting relationships between stratiform chert veins and cross-cutting dykes can be observed, which is rarely the case, stratiform veins postdate dyking (Fig. 9d).

Carbonaceous matter in both banded cherts and chert dykes and veins consists of equant, sand-sized carbonaceous grains that are moderately packed (Fig. 6e). Veins and dykes contain, in addition, sand-sized fragments of the host rock, including quartz, which are frequently completely replaced by chert. Botryoidal translucent cherts are devoid of carbonaceous matter, except for thin, carbonaceous chert laminae along vein margins.

Interpretation: Of importance in the context of this study is the origin of black chert dykes and veins below, and at the base of, the BRC and any possible genetic link to the overlying, unusually thick sequence of banded cherts. The most plausible interpretation for the origin of stratiform chert veins is to regard them as fractures that were initiated by overpressured hydrothermal fluids and were filled by hydrothermal chert and sediment-derived material. Such an origin is indicated by the bedding-parallel orientation, brecciation of the host rock, the local filling of veins by botryoidal chert, and local host-rock replacement. Chert dykes are equally interpreted as hydrothermal features that recorded multiple injections of fluidized sedimentary material and hydrothermal fluids, partly brecciating the host rock and incorporating host-rock fragments into the dyke. Stratiform veins and cross-cutting chert dykes probably formed during a single event, although the veins formed slightly later.

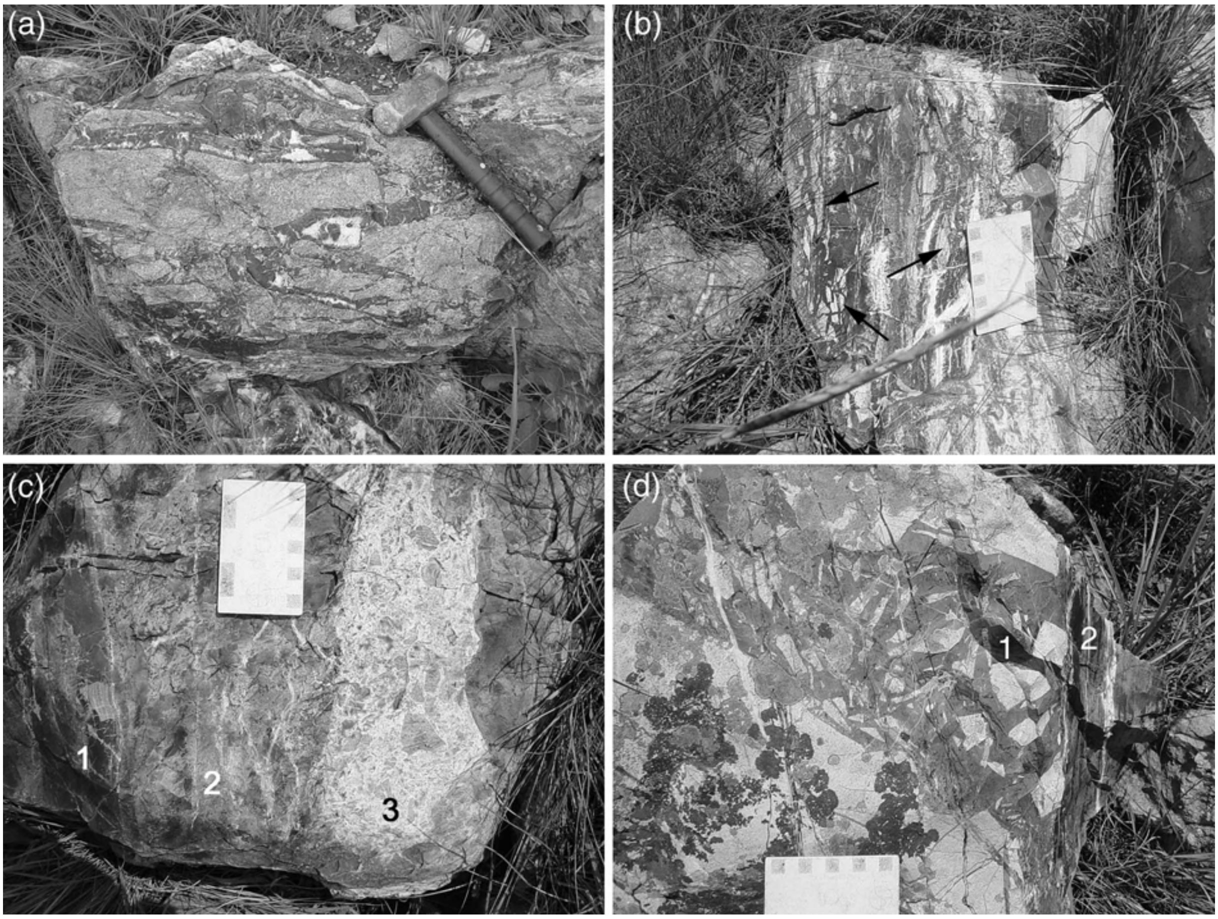

Figure 9. *(a) Silicified dacitic sandstone transected and brecciated by stratiform veins of black and botryoidal chert. (b) Banded chert consisting of multiple stratiform veins, as indicated by angular fragments of dacitic host rock (arrows). (c) Dyke consisting of (1) laminated black chert, (2) massive black chert with fragmental texture, and (3) weathered translucent chert with angular black chert fragments. Layering is parallel to dyke walls (not seen in photograph), which are perpendicular to stratification of the host rock. (d) Black chert dyke with fragments of massive dacitic host rock (1) cut by stratification-parallel black chert vein (2) showing lamination.*

Chert veins and dykes were not observed above the basal evaporitic facies of the BRC. This may indicate that hydrothermal activity was ongoing while this facies was being deposited and ceased before deposition of the overlying cherts, or that the evaporitic facies acted as a barrier for ascending and/or laterally migrating hydrothermal fluids. Cessation of hydrothermal activity can be attributed to reduced convection of seawater through the underlying rocks, when the basal chert beds prevented continuous recharge of the hydrothermal system. Banded cherts above the evaporitic facies show soft-sediment deformation (Tice and Lowe, 2004) and may have become lithified relatively late in the depositional history. They were thus unable to act as an impermeable barrier and did not respond to hydrothermal activity by brittle fracturing. The formation of chert-clast breccias near the base of the BRC is best attributed to subsurface dissolution of evaporites by hydrothermal fluids rather than to evaporite dissolution in the phreatic zone (Lowe and Fisher Worrell, 1999). This interpretation is in line with the presence of botryoidal chert veins in the volcaniclastic facies that are similar to the "evaporite dissolution cavities", thus suggesting a relationship between evaporite dissolution and hydrothermal activity.

Kromberg Formation - K3c

Banded sedimentary cherts (K3c of Lowe and Byerly, 1999) overlying silicified volcanic rocks at the top of the Kromberg Formation (Fig. 2) are exposed in several localities of the BGB. The cherts and associated rocks form a locally very well exposed, laterally traceable horizon that has been investigated in the central study area and on Josefsdal farm.

Central study area

Description: In the central study area (Fig. 3, locality 5), the section commences with silicified pillowed basalt that contains cm-wide black chert dykes at the top (Fig. 10). Basalt is overlain by black and white banded chert; black and botryoidal chert veins are common. The chert is succeeded by pillow basalt that is variably replaced by black, massive chert and minor green chert. Black chert occurs in diffuse patchy areas or in stratification-parallel horizons. Black chert veins parallel, perpendicular, and random to stratification are abundant. A few metres thick and locally sheared banded chert overlies basalt and is followed by a sheared fuchsite-chert-carbonate rock.

The same section *c.* 1.5 km to the east (Fig. 3, locality 6) has a similar stratigraphy (Fig. 10). It starts with a succession of silicified pillow and massive basalt. Stratification-parallel as well as irregular veins and patches of chert occur in the uppermost 5 m. Opaque black chert occupies the centre of patches and veins, whereas translucent black chert forms a *c.* 3 mm-wide zone along the typically cuspate contact (Fig. 11a). Basalt is succeeded by sedimentary rocks, including laminated black chert and a massive conglomerate that consists of silicified basalt pebbles in a matrix of translucent chert. Pebbles show marginal chert replacement, and some chert veining opened up the original clast-supported fabric. The conglomerate is overlain by a succession of banded, laminated and massive, grey and black cherts that include stratiform veins. Cross-cutting black chert veins transect this unit and the underlying conglomerate and partly brecciate it (Fig. 11b). Rock fragments show evidence of marginal replacement by chert and are frequently surrounded by translucent chert rims. The chert sequence is overlain by poorly exposed komatiitic basalt, a sheared unit of banded black chert, and a prominent horizon of fuchsitic chert with numerous irregular chert veins and patches.

Interpretation: Banded chert horizons represent silicified sediments that were laid down in between submarine volcanic activity. Deposition took place in a low-energy, sub-wave base setting with episodic, high-energy current events that resulted in the deposition of conglomerate beds. Many black chert veins and dykes formed after lithification of the banded cherts, resulting in fracturing and brecciation. The veins are considered to be of hydrothermal origin, as indicated by the geometry of the fracture pattern and the replacement of both volcanic and sedimentary host rocks. Chert veining associated with brecciation of bedded cherts is a result of fracturing of the impermeable barrier horizon allowing ponded, overpressured fluids to pass through.

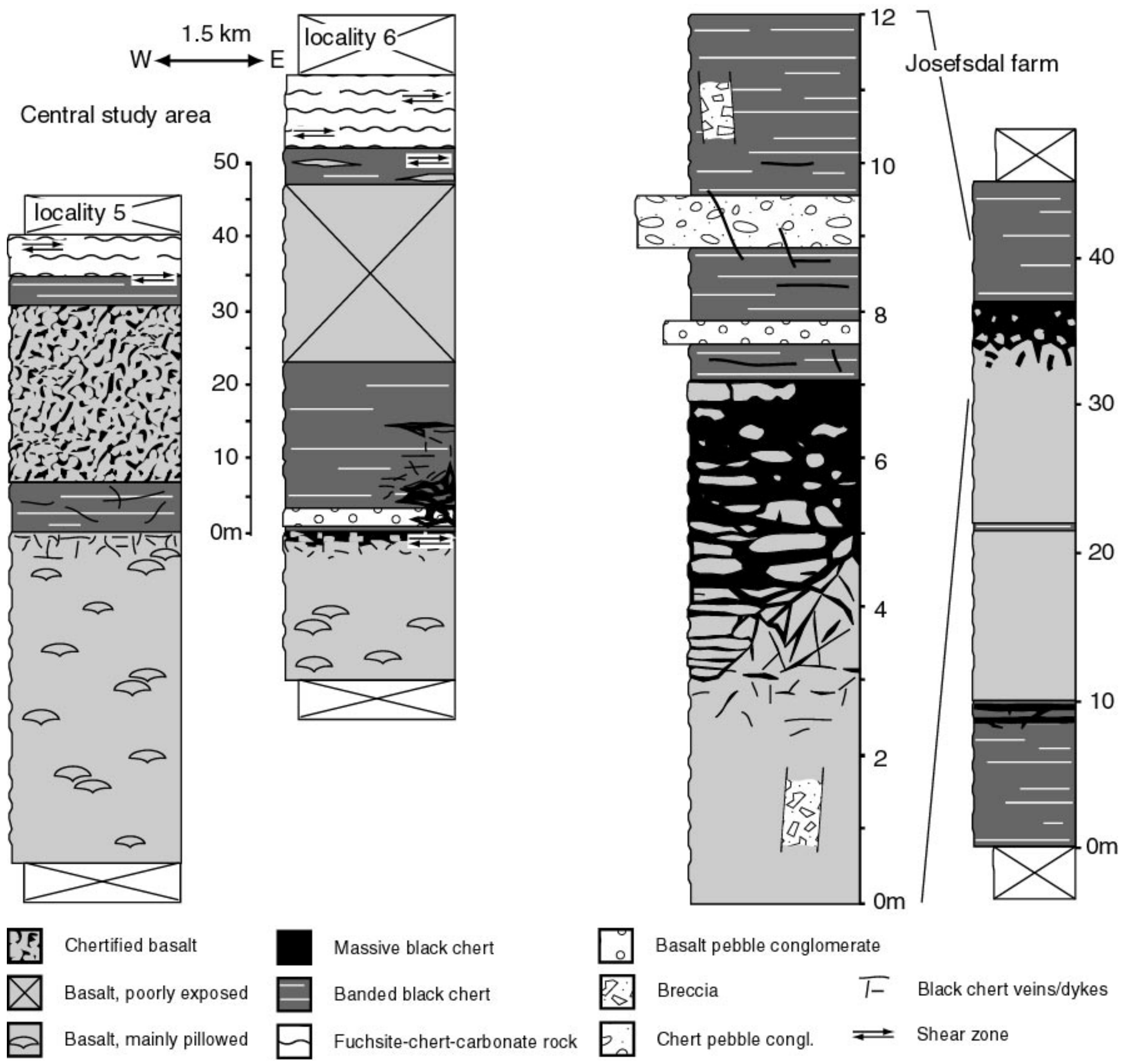

Figure 10. *Simplified stratigraphic sections of chert horizon K3c at the top of the Kromberg Formation in the central study area (localities 5 and 6, Fig. 3) and on Josefsdal farm (locality 7, Fig. 1).*

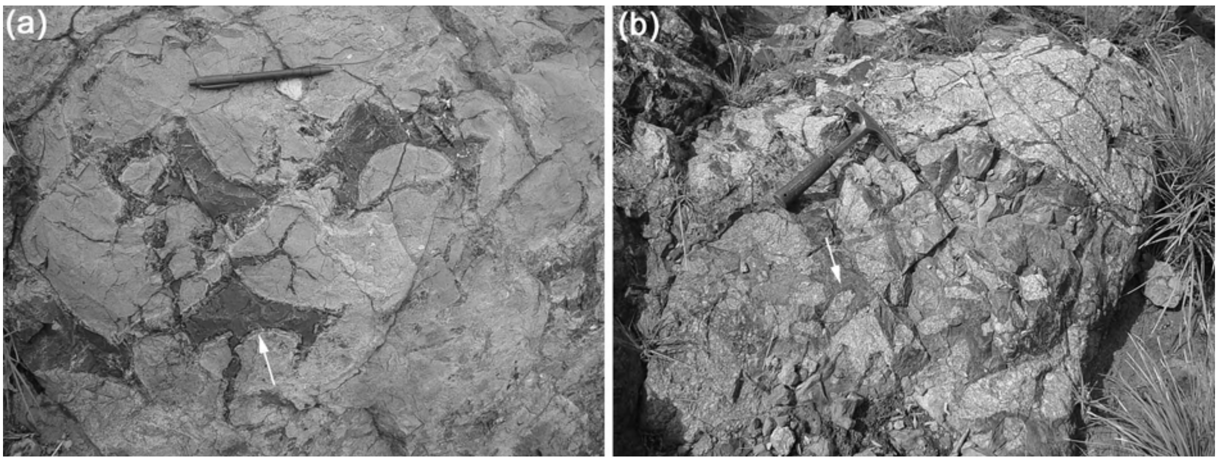

Figure 11. *(a) Amoeboidal patches of black chert in massive silicified basalt. Note the rim of translucent chert along basalt contacts (arrow). (b) Basalt pebble conglomerate transected and brecciated by black chert dykes. Some breccia fragments show evidence of marginal replacement by black chert (arrow).*

Josefsdal farm

Description: Silicified volcanic rocks and banded cherts of the uppermost Kromberg Formation also crop out on Josefsdal farm (Fig. 1, locality 7) *c*. 12 km east-southeast of the previous study area. The section (Fig. 10) starts with laminated greenish-grey and black chert; some laminae contain accretionary lapilli. Stratiform black chert veins, some of which cross-cut bedding, are common at the top of the unit. Banded chert is overlain by a massive, greenish-grey chert, which represents silicified komatiitic basalt (Hofmann, unpubl. data). Millimetre-wide, discontinuous veins of translucent chert give rise to a lenticular fabric (Fig. 12a). Irregular veins (Fig. 12b), dykes and patches of black chert are common in the uppermost few metres of the silicified basalt and increase in abundance upsection (Fig. 10). Near the top, veins can no longer be discerned, and carbonaceous chert surrounds basalt fragments (Fig. 12c). The irregular shape of some fragments is related to marginal replacement by black chert. Black chert reveals a fragmental texture when weathered. This texture is related to silt- to fine pebble-sized, angular to rounded, probably mostly wall rock fragments.

Chert-veined basalt is succeeded by parallel-laminated, carbonaceous grey chert. The contact is very sharp; the underlying chert does not cut through it, except for a later generation of translucent chert veins. A bed of massive basalt pebble conglomerate occurs near the base of the sedimentary sequence (Fig. 10) and is infiltrated by botryoidal chert; chert clasts are absent. A second bed of massive conglomerate (Fig. 10) comprises clast-supported, very well-rounded pebbles and cobbles of grey chert. The sedimentary sequence is transected by a network of mostly bedding-parallel veins of black chert (Fig. 12d). Veins below the conglomerate frequently contain clasts derived from this bed.

Patches of grey chert and basalt-clast breccia occur in the uppermost part of the basalt sequence (Fig. 12a). A similar breccia exists as a dyke filling in the overlying sedimentary sequence. The breccia consists of angular chert clasts and rounded chert fragments, the latter derived from chert-pebble conglomerate.

In thin section, banded chert consists of a silicified clay-/siltstone with detrital quartz and disseminated, somewhat compacted, very fine sand-sized carbonaceous grains (Fig. 6f). Vein chert in basalt consists predominantly of tightly packed, fine sand-sized carbonaceous grains.

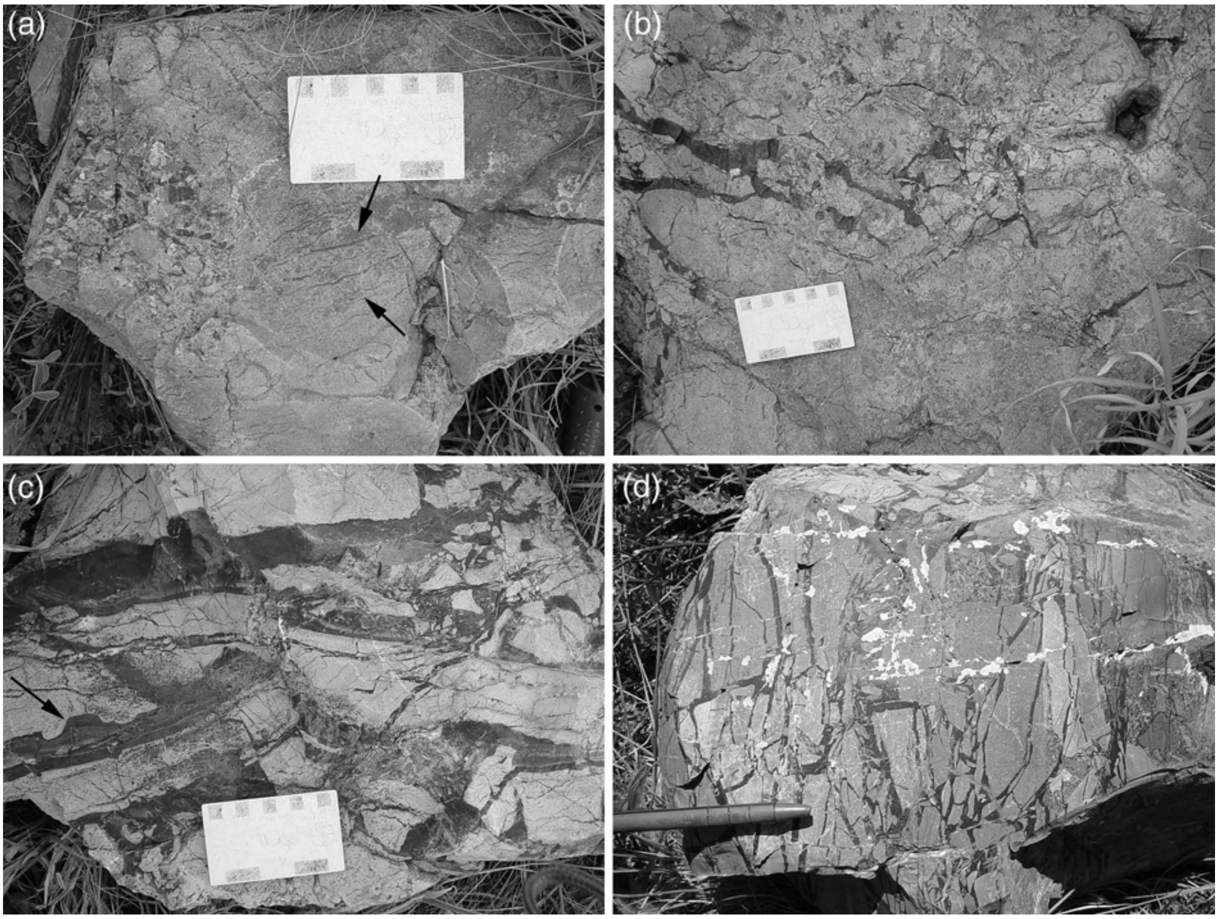

Figure 12. *(a) Silicified basalt with translucent chert veins (arrows). Breccia of silicified basalt and chert fragments (left centre) probably represents a fissure filling. (b) Thin black chert veins transecting silicified basalt. (c) Black chert-veined and brecciated silicified basalt. Note local replacement of basalt by black chert (arrow). (d) Grey banded chert brecciated by thin black chert veins. Some chert veins contain rounded clasts derived from an overlying chert conglomerate bed.*

<u>Interpretation</u>*:* Stratiform chert veins at the chert-basalt contact suggest minor fluid flow along this contact after deposition of the lava flow. Hydrothermal activity was, however, much more pronounced along the contact with the overlying banded chert and resulted in much of the basalt being fractured and replaced.

The association of chert-pebble conglomerate and veins filled with rounded chert clasts has been described by Paris *et al*. (1985) and Stanistreet and Hughes (1984), who regarded such rocks as pseudoconglomerates that formed as discordant subsurface breccia bodies during exhalative processes. This and similar conglomerate bodies are more likely of sedimentary origin, because they form continuous beds and sometimes show grading. Rounding of the clasts took place in a "normal" sedimentary environment and not as a result of mechanical wear during hydrothermal transport. The presence of rounded chert fragments in discordant veins has been explained by Lowe (1999a) as a result of early brecciation of the cherty sediment and filling of the fractures by debris from overlying, still unlithified conglomerate beds. Lowe (1999a) noted that the absence of fragments of underlying rock in the breccias and of breccias intrusive into overlying units indicate that they were not formed by upward fluid flow. Brecciation has been attributed to exposure and desiccation or hydrofracturing during sediment dewatering, either as a result of compaction or boiling of interstitial waters during the deposition of overlying lavas (Lowe, 1999a). It is more likely that brecciation is a result of syndepositional hydrothermal activity that resulted in the formation of fractures that were then infilled by partly unconsolidated sediments. Fissures that are filled with brecciated host-rock material must have formed some time after deposition and lithification of the banded cherts, because they lack carbonaceous chert fillings, and probably represent hydrothermal breccia dykes. Similar breccia dykes have locally been observed at the Onverwacht-Fig Tree contact, where they contain fragments derived from stratigraphically underlying units (Hofmann, unpubl. data).

Barite Valley Syncline (BVS)

Description: Sedimentary horizons, stratiform veins and cross-cutting dykes of carbonaceous cherts are common in the southern part of the BVS (Fig. 1, locality 8), where the contact between the Onverwacht and Fig Tree Group is well exposed (Fig. 13). The stratigraphy and sedimentology of Fig Tree strata in the BVS have been described by Heinrichs and Reimer (1977) and Lowe and Nocita (1999). As pointed out by Lowe and Byerly (2003), the BVS is not a true syncline, as the two limbs are separated by faulting and show a different stratigraphy. The strata of the two limbs are dipping steeply to the east-southeast (Fig. 13). Open to tight folding is common in the central part of the structure, and fold axes have a shallow to moderate plunge to the north-northeast.

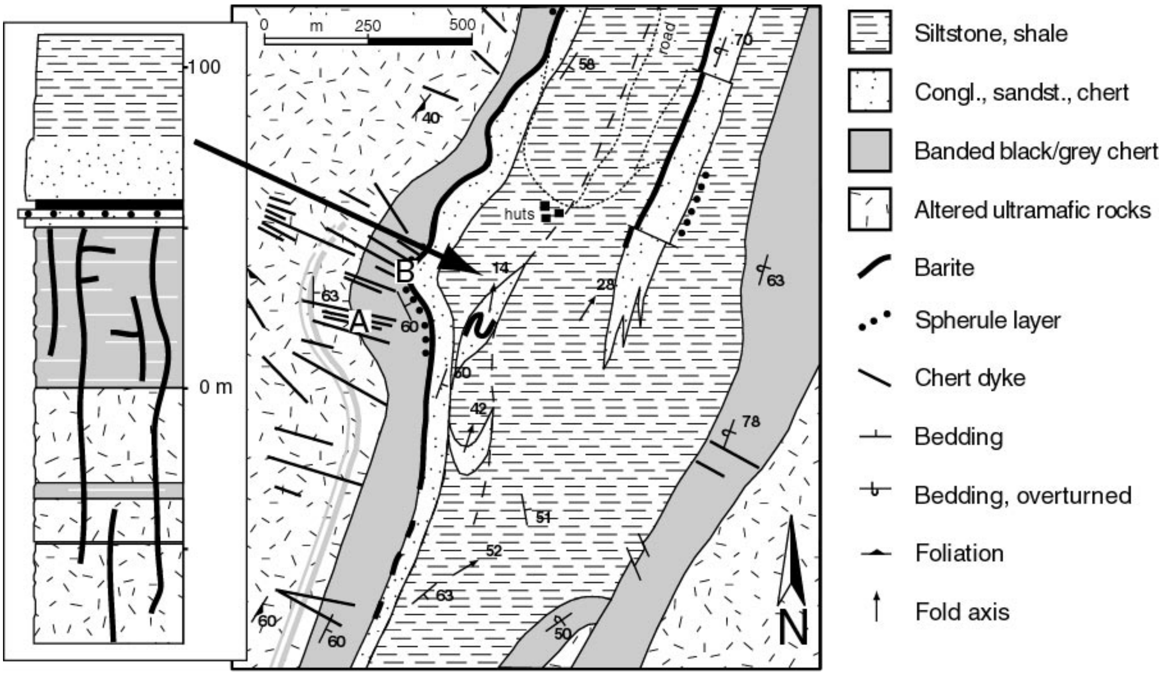

Figure 13. *Geological map of the southern part of the Barite Valley Syncline and stratigraphic section of the western limb (Heinrichs and Reimer, 1977; Lowe and Byerly, 2003; own mapping). A and B are localities discussed in the text.*

On the west limb, the lowermost stratigraphic unit consists of intensely altered ultramafics, now represented by a fuchsite-chert-carbonate rock (Fig. 13). A sequence of banded black, grey and white chert overlies the volcanic rocks. When weathered, this unit has the appearance of silicified shale and siltstone. White-weathering translucent chert bands mostly represent stratiform veins. Numerous chert dykes cut through the sedimentary and underlying volcanic rock units. Banded chert is overlain, possibly along an erosional unconformity (Lowe and Byerly, 2003), by a lithologically complex unit of massive greenish-grey chert with mm-wide translucent chert veins, fine chert-pebble conglomerate and grit containing meteorite impact spherules (Lowe *et al*., 2003), and bedded barite intercalated with silicified sandstones. Chert dykes do not penetrate this unit. This is overlain by interstratified silicified sandstone, fine chert-pebble conglomerate, barite, and jaspilite, followed by parallel-laminated tuffaceous sandstone, siltstone and shale. The relationships discussed below refer to the west limb of the BVS.

Chert dykes are up to 3 m wide, relatively tabular and extend for at least 250 m downsection. They dip steeply to the south-southwest and terminate along a greenish-grey chert horizon that is situated immediately below the impact spherule and barite beds. This chert horizon contains abundant diffuse patches of black translucent chert.

Metre-scale chert dykes are frequently composite dyke-in-dyke structures (Fig. 14a) and consist of discrete generations of dyke fillings, thus showing a crude layering subparallel to the dyke walls. They are filled with massive carbonaceous chert, botryoidal chert and a common carbonaceous chert variety that, when weathered, reveals a fragmental texture. This texture is related to the presence of mostly granule- to pebble-sized (but from silt to cobble-sized), angular- to well-rounded, silicified clasts that float in the chert matrix. The fragments are compositionally similar to the immediate dyke host rock. Some fragments show evidence of *in situ* brecciation by thin chert veining, as indicated by the preservation of a jigsaw fit (Fig. 14b). Black chert fragments also occur and they most likely represent fragments of an earlier chert dyke generation. Although most clasts are angular, some are subangular to well rounded, so that some dyke fills resemble matrix-supported conglomerates. Mutual cross-cutting relationships between different generations of carbonaceous and botryoidal translucent cherts are common. Dyke walls are sometimes irregular, suggesting marginal chert replacement. Patches of translucent chert occur in some carbonaceous chert dykes in between the fragments, suggesting incomplete filling of dykes at times.

Bedding-parallel chert veins that locally branch off the dykes (Fig. 14c) are common in silicified sediments. These veins are up to 0.5 m wide and transect and brecciate the host rock subparallel to bedding. Stepping of chert dykes and veins both vertically and laterally is common (Fig. 15). At one locality a black chert dyke occurs that cuts through bedding at a low angle; black chert is finely laminated parallel to the dyke wall.

Several dykes, irrespective of the nature of the immediate wall rock, contain equant to tabular, angular to rounded pebbles of black, slightly translucent chert in a matrix of carbonaceous chert. One dyke that cuts across banded chert contains angular fragments of the host rock that are surrounded by a 5 mm-wide rim of botryoidal chert, resulting in a more rounded shape of the fragments (Fig. 14d). The same dyke, 1.5 m downsection, contains spherical pebbles of translucent chert that are rimmed by botryoidal chert, with the same shape and size as the chert-rimmed angular clasts (Fig. 14e).

At location A (Fig. 13), a swarm of densely spaced chert dykes transects the base of the sedimentary sequence, which contains abundant jaspilite beds in otherwise black and white banded chert in a zone $\geq$ 4 m thick. The dykes contain jaspilite fragments where they cut the jaspilite-bearing horizon, but jaspilite fragments also occur stratigraphically below the horizon. Furthermore, jaspilitic cherts are cross-cut by small veins of black chert both parallel and perpendicular to bedding; the banded cherts are frequently replaced along the margin of these veins (Fig. 14f). Approximately 10 m below the impact spherule layer at locality B (Fig. 13) occur spherules in several black chert dykes in a bedding-parallel, poorly exposed zone with a minimum lateral extent of 10 m and a thickness of *c.* 3 m. The spherules either float in black chert or form rock fragments composed entirely of spherules.

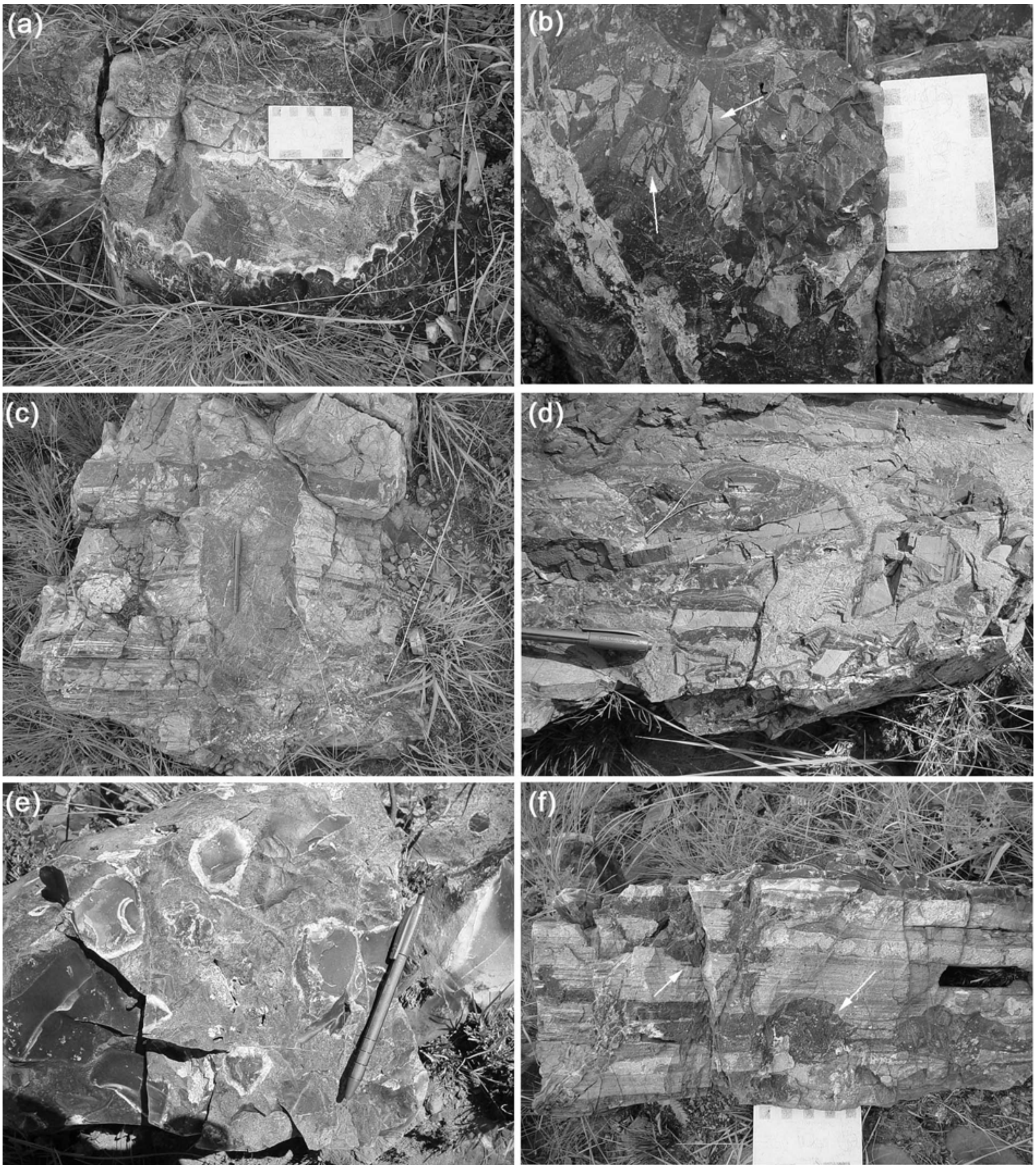

Figure 14. *(a) Chert dyke consisting of botryoidal chert at the margin and a later fill of carbonaceous chert in the centre. (b) Chert dyke containing fragments of silicified sedimentary host rock in a black chert matrix. Some fragments have been fractured by thin chert veins after being incorporated into the dyke (arrows). (c) Dyke of massive black chert that transects silicified sedimentary rocks and branches into a stratiform vein upsection. Stratigraphic way-up is to the top. Picture taken on east limb of the Barite Valley Syncline. (d) Angular fragments of silicified sedimentary rock that are rimmed by translucent, laminated and somewhat botryoidal chert, resulting in a more rounded shape of the fragments. (e) Angular to rounded pebbles of black translucent chert in a fragmental black chert matrix. Pebbles are rimmed by megaquartz. (f) Banded jaspilitic chert intruded and partly replaced (arrows) by black chert.*

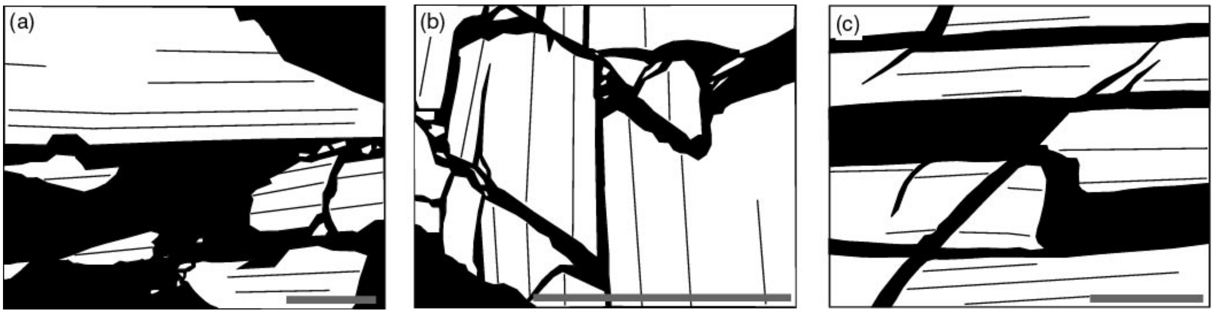

Figure 15. *Field relationships between silicified sedimentary rocks (bedding is indicated) and intrusive veins and dykes of massive carbonaceous chert. Scale bars are 10 cm long.*

Bedded carbonaceous cherts represent silicified siltstones and claystones that contain remnants of silt-sized quartz grains. Carbonaceous matter occurs in the form of slightly compacted, ellipsoidal grains in the very fine sand-size range. Chert dykes contain abundant silt to coarse sand-sized, equant carbonaceous grains admixed with some angular, chert-replaced clasts, representing either detrital grains or wall-rock fragments.

Interpretation: Chert dykes and veins are interpreted to have been initiated by hydrothermal processes, on the basis of similar arguments presented earlier, such as fracturing of the wall rocks, geometry of the chert-filled fractures, multiple dyke fillings and *in situ* brecciation of earlier generations of dyke fillings, marginal replacement of wall rock and wall-rock fragments, and the presence of botryoidal chert. Furthermore, the presence of vertical dykes that branch into bedding-parallel veins, and the presence of dykes with a parallel laminar fabric that are at an angle to bedding indicate that the dyke system cannot be regarded as simple open fissures that were infilled with sedimentary material from above.

Rounding of wall-rock fragments is a common observation in the chert dykes. It has been shown that rounding can be a result of marginal replacement of angular fragments and that many chert pebbles represent completely replaced wall-rock fragments. Rounding of fragments in hydrothermal breccias is commonly observed and may be a result of mechanical abrasion during movement in the fluid, or, as it is the case here, be a result of corrosive wear, i.e., the marginal dissolution of fragments (Jebrak, 1997). It cannot always be ascertained if rock fragments in chert dykes were derived from the immediate wall rock, including an earlier chert generation of the dyke fillings, or from rocks stratigraphically above or below the position they occur. The presence of jaspilite fragments and impact spherules in dykes below beds that contain such material suggests some downward movement (see also Lowe and Byerly, 1986). In most cases, however, the fragments are derived from the immediate wall rocks and appear not to have travelled far up- or downsection.

Chert dykes do not penetrate a laterally persistent horizon of greenish-grey chert and extend into the overlying conglomerate and barite beds. This contact has been regarded as possibly unconformable, and it may thus be plausible that the termination of the chert dykes, if regarded to be of syndepositional origin, is a result of erosion down to that contact. However, a similar relationship exists on the east limb, where chert dykes stop along a chert horizon along which there is no evidence for an erosional contact. Furthermore, chert dykes are not terminated sharply, but rather lose their geometry to form diffuse patches of black chert in green chert. These relationships suggest that the chert dykes terminated at a stratigraphic level of early silicified sediments that were impermeable for the hydrothermal fluids. The chert dykes are not vertical, but dip steeply to the north-northeast, which is probably related to the north-northeast plunge of the fold structure, suggesting that they formed in a vertical orientation.

The field relationships in the BVS do not clearly permit identification of the exact timing of the hydrothermal activity. However, it has to be kept in mind that the sedimentary sequence above the chert dykes contains several beds of barite. The beds are interpreted to consist of detrital barite that was eroded from hydrothermal barite deposits elsewhere (Heinrichs and Reimer, 1977). Hydrothermal barite is commonly associated with chert dykes in the Pilbara Craton (Nijman *et al*., 1999), possibly suggesting a genetic link between chert dykes and reworked barite, i.e., syndepositional hydrothermal activity.

Msauli Chert

The Onverwacht-Fig Tree contact is locally occupied by a chert unit that consists of silicified beds of accretionary lapilli, termed the Msauli Chert. Two sections have been studied in detail, the type section in the Msauli gorge and a section situated in the central study area.

In the Msauli gorge (Fig. 1, locality 9), the section starts with a lenticular-banded, fuchsite-chert-carbonate rock (Fig. 16a) that represents altered ultramafic rocks of the Mendon Formation. The volcanic rocks are sharply overlain by the Msauli Chert, which, in the lower part, consists of thinly interbedded green and black carbonaceous chert. This unit is overlain by accretionary lapilli-bearing, normally graded and rarely cross-stratified beds intercalated with laminated green chert (Heinrichs, 1984; Lowe, 1999b). The Msauli Chert and underlying volcanic rocks are transected by massive carbonaceous and botryoidal translucent chert veins and dykes mostly parallel and perpendicular to bedding (Fig. 16a). In most cases, stratiform veins consist of botryoidal chert and formed later than the carbonaceous chert dykes. Some dykes are represented by a network of mm- to cm-scale veins that surround angular host-rock fragments, with large fragments being unrotated and almost *in situ*. Other dykes show an irregular lamination parallel to the dyke walls (Fig. 16b). They may contain elongate fragments of wall rock that are aligned parallel to the lamination. The Msauli Chert is overlain by *c.* 5 m of rather massive, but poorly exposed, carbonaceous chert, followed by variably silicified graphitic shale. No chert dykes were observed that cut the shale unit. Microfossil-like features showing apparent cell division have been reported from carbonaceous rocks of the Msauli Chert (Knoll and Barghoorn, 1977).

An additional outcrop of Msauli Chert has been investigated *c.* 5 km east of the previous section in the central study area (Fig. 3, locality 10). The stratigraphy of the Msauli Chert and associated rocks is very similar, although the whole unit is locally tectonically duplicated due to low-angle faulting (not shown on map). The exposed section starts with a schistose fuchsite-chert-carbonate rock containing abundant, mostly foliation-parallel veins of botryoidal chert (1-30 cm wide). Layers (5-30 cm thick) with undeformed spinifex textures indicate a komatiite parentage for the rocks. The altered ultramafics are overlain by *c.* 20 m of interbedded lapillistone and green chert (Msauli Chert). The Msauli Chert is transected and brecciated by carbonaceous and botryoidal chert veins that are mostly subparallel to bedding. Some chert veins are exactly parallel to bedding and are filled with chert that may show a parallel laminar fabric (Fig. 16c). The uppermost 1-2 m of the Msauli Chert is strongly brecciated by a network of bedding-parallel veins of botryoidal chert. The chert penetrates lapillistone along the margin and either displaces individual lapilli outwards or replaces the finer-grained matrix material so that originally densely packed lapilli become matrix-supported in black chert (Fig. 16d). The Msauli Chert is overlain by *c.* 10 m of banded black and white chert. Some chert layers are well banded, whereas other layers are faintly laminated to massive and may represent stratiform veins. Bedding-parallel botryoidal chert veins are present. In addition, there are cross-cutting black chert dykes, although they are not as common and/or easy to detect as in the underlying Msauli Chert. A chert-pebble conglomerate is intercalated with massive black chert near the top of the section. This bed is invaded by translucent chert, which results in the clast-supported fabric being opened up. The conglomerate becomes sheared out laterally, although there is no clear shear fabric in either the conglomerate or the black chert. However, black chert contains silicified, poorly visible clasts that are probably derived from conglomerate, indicating that some of the material may have been replaced by chert. The chert unit is overlain by shales of the Fig Tree Group, although the contact is not exposed at this locality.

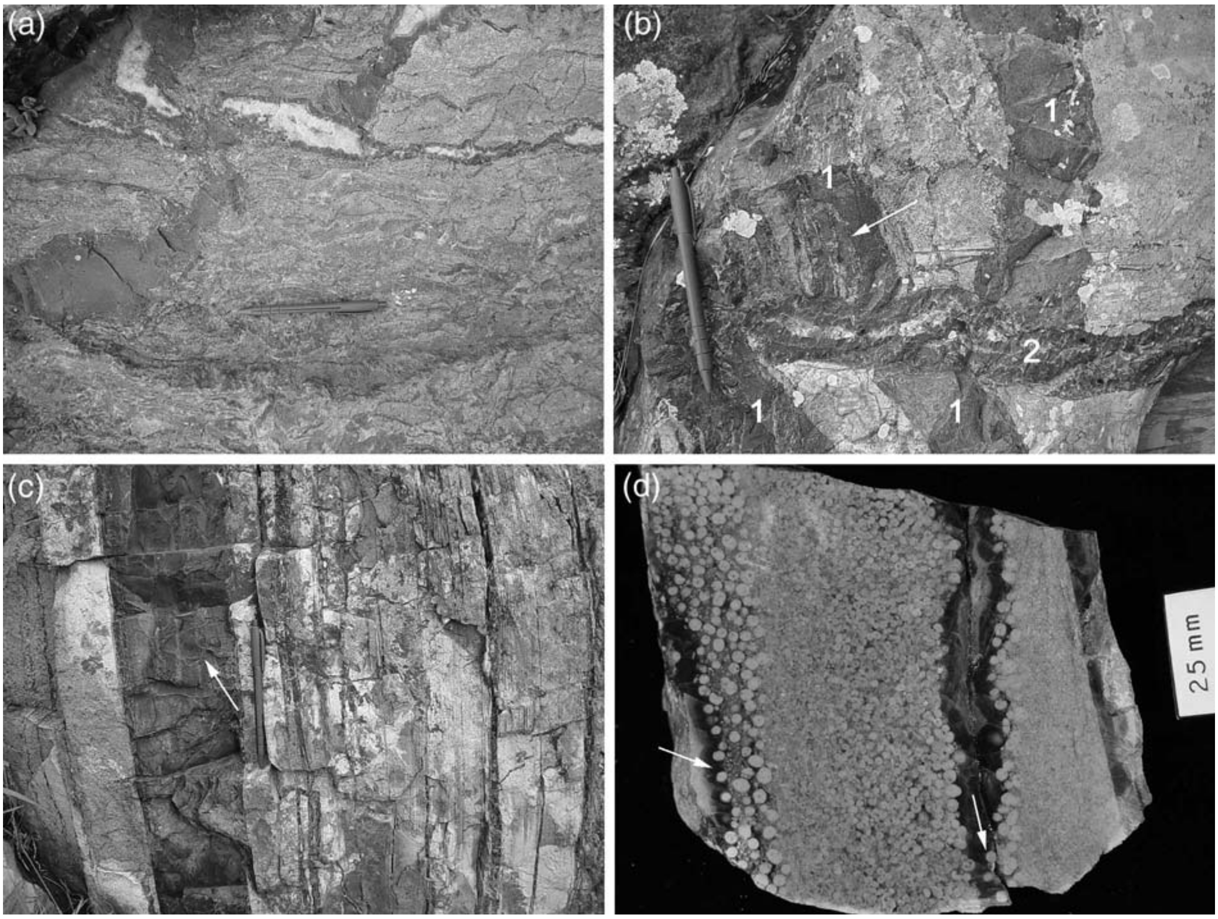

Figure 16. *(a) Lenticular-banded, altered ultramafic rock transected by carbonaceous and botryoidal chert dykes and veins. (b) The Msauli Chert is cut by carbonaceous chert dykes (1) at an angle to bedding. Some dykes show a crude stratification parallel to the dyke walls (arrow). A later vein of black botryoidal chert (2) transects the rock subparallel to bedding. (c) Black chert vein intrusive into parallel-stratified Msauli Chert. The chert vein shows a fine lamination parallel to the vein walls (arrow). (d) Lapillistone transected by botryoidal chert veins. Note that chert infiltrates the lapillistone along the vein margin and displaces individual lapilli outwards (arrows).*

<u>Interpretation:</u> Both carbonaceous and botryoidal cherts are interpreted as hydrothermal fracture fillings that formed during the same hydrothermal event, although botryoidal chert frequently, but not always, formed later. The presence of wall-rock fragments aligned parallel to a commonly developed layering in the dykes indicate that the dykes and their stratification is a result of multiple chert injections. The fracture pattern and brecciation of the uppermost part of the Msauli Chert in the central study area suggests a hydraulic fracturing mechanism, with the hydrothermal fluids again concentrated below a lithological contact. Translucent chert invaded lapillistone and conglomerate beds and there is evidence that this invasion may have led locally to "delithification", as in the case of accretionary lapilli becoming entrained in the chert. The parallel laminar fabric of some bedding-parallel chert veins is probably a compaction or foliation feature, which could easily be confused with a sedimentary structure. There is evidence for shearing along massive black chert units, as indicated by deformation of one conglomerate horizon, suggesting that massive black chert horizons may host cryptic bedding-parallel shear zones.

Central Study Area, Fig Tree-Onverwacht Contact

<u>*Description:*</u> The contact between the Fig Tree Group and tectonically overlying Onverwacht Group is represented by a shear zone (Granville Grove Fault of Lowe and Byerly, 1999), along which the sedimentary and volcanic rocks have been silicified to black chert. The uppermost exposed sedimentary rocks of the Fig Tree Group, which are characterized by a homogeneous sequence of parallel-laminated and rarely cross-bedded, fine-grained sandstone, are silicified to finely banded, grey-weathering, relatively opaque black chert (Fig. 17a). Thin veins of massive black chert, up to 5 cm wide, cross-cut the lamination locally. Silicification took place in an at least 30 m-wide alteration zone beneath the contact with tectonically overlying pillow basalts of the Mendon Formation. On average, silicification intensifies towards the contact, although stratiform horizons of only poorly silicified sedimentary rocks may occur within the alteration zone.

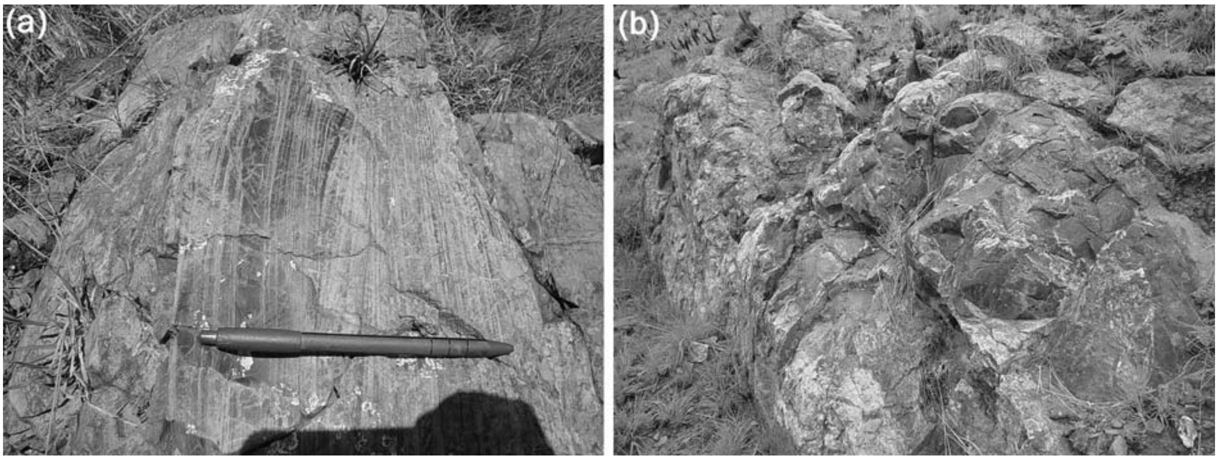

Figure 17. *(a) Parallel- and cross-laminated carbonaceous chert* c.*15 m below the shear zone. Stratigraphic way-up is to the right. (b) Silicified pillow basalt consisting predominantly of massive black chert.*

Near the contact the silicified sedimentary rocks become complexly folded, ferruginized and intercalated with sheared shaley gossans that contain some scattered chert lenses. The contact itself is a 1 m-wide, highly strained gossan that shows an anastomosing foliation and a mylonitic fabric.
The shear zone is overlain by a *c.* 30 m-thick zone of altered volcanic rocks, mostly pillow basalts, which are completely replaced by chert locally (Fig. 17b). Silicified volcanic rocks consist of black chert with fragments and diffuse patches of green chert. Silicification of the volcanic rocks is not continuous along the contact, and pillow basalt may be carbonated or Fe-oxide impregnated at other localities.

In thin section, silicified sandstone consists predominantly of chert with many silt- to fine sand-sized quartz grains that withstood alteration to chert. Carbonaceous matter is absent, whereas disseminated idiomorphic sulphide grains do occur. Silicified basalt consists almost totally of chert that is present as angular fragments and matrix. Disseminated clots of carbonaceous matter are rare.
<u>*Interpretation:*</u> The shear zone is a result of thrusting of Onverwacht Group rocks onto Fig Tree strata. That Fig Tree rocks were silicified adjacent to the shear zone is indicated by: (1) discontinuous or variably intense silicification of rocks adjacent to the shear zone vertically; (2) similar lithological attributes of the silicified sedimentary rocks compared to the underlying rocks (e.g., homogeneous coloration and lamination style); and (3) clear younging indicators in silicified rocks immediately below the shear zone. There is no evidence for a shear zone below the silicified rocks and that these cherts are part of an older chert sequence that was brought into place by folding (e.g., Lowe *et al.*, 1999). Silicification of the overlying volcanic rocks is also related to the contact, because it intensifies downsection towards the contact. The alteration of sedimentary and

volcanic rocks to chert along an unequivocal shear zone indicates that the alteration is a result of hydrothermal fluids that were channelled along the shear zone. Ferruginization of chert, and the shearing and brecciation in the gossaneous zone must have taken place *after* silicification. The gossan is a result of sulphide weathering, and the sulphides were probably introduced during reactivation of the shear zone during a later deformation event.

DISCUSSION AND CONCLUSIONS

Carbonaceous cherts in the BGB span a time interval of more than 200 Ma. Despite this, they share very similar lithological attributes and relationships to surrounding rocks, suggesting that they formed by a common process. Sedimentary chert horizons are very continuous laterally. They always overlie volcanic and volcaniclastic rocks that are silicified in the uppermost few tens of metres. Geochemical evidence has been presented that this silicification is a result of low-temperature (≤ ~150 °C) hydrothermal processes. Seawater, which was close to saturation with respect to amorphous silica (Siever, 1992), is thought to have circulated through the seafloor volcanics. The heat for convection was probably provided by a high regional heat flow during the early and mid-Archaean (Hofmann, 2005b). Precipitation of silica took place as a result of a decrease in silica solubility, when diffusely upflowing hydrothermal fluids came into contact with seawater near the seafloor. This resulted in the silicification of volcanic rocks close to the seafloor and the silicification of overlying biogeneous and tuffaceous sediments near the sediment-water interface (Hofmann, 2005b). Both rock types were affected by very similar chemical alteration processes, which resulted in the formation of very similar textural features. For example, translucent chert veins are a characteristic feature of altered ultramafic rocks, such as those underlying the Msauli Chert (Fig. 16a). The same veinlets are common in silicified rocks of ultramafic composition throughout the volcano-sedimentary sequence, including the massive green cherts in H3c that represent komatiitic tuffs. It also needs to be emphasized that alteration and silicification involved a variety of rocks types, including ultramafic volcaniclastic deposits below chert horizon K1c1, and dacite-derived conglomerates and sandstones below the Buck Reef Chert. The protolith did, therefore, not play a role for alteration zones to develop. Important was the presence of sedimentary chert beds overlying these zones.

Chert dykes play an important role in the understanding of the hydrothermal processes involved, because they provide evidence that these processes took place just below the seafloor and not during much later, post-burial hydrothermal activity. Carbonaceous matter in the chert dykes is petrographically identical to the kerogen in the sedimentary horizons. The presence of certain clasts admixed with the kerogen in the dykes, which were derived from overlying beds (such as impact spherules, Lowe and Byerly, 1986), suggests that the bulk of the carbonaceous matter was derived from sedimentary material that accumulated on the seafloor. The dykes do, therefore, not represent hydrothermal feeder channels for the sedimentary cherts, in a way analogous to modern seafloor hot spring deposits. But, neither can they be regarded as simple fissures that were filled by carbonaceous sedimentary material. Many veins contain angular host-rock fragments and show hydraulic fracture patterns, suggesting that they were initiated by the forceful intrusion of over-pressured hydrothermal fluids. Observations, such as branching of dykes into stratiform veins, wall-rock replacement, multiple-dyke fillings, and *in situ* brecciation of earlier generations of dyke fillings, supports this view.

But how did the hydrothermal systems become over-pressured when they formed close to the seafloor? This can be explained by early silicification of seafloor sediments by hydrothermal activity. Syndepositional silicification of sedimentary deposits resulted in the formation of impermeable pathways for ascending hydrothermal fluids. Buildup of fluid pressure beneath the cap rocks resulted in ponding of hydrothermal fluids and breaching and brecciation of the cap rocks at times. This resulted in the formation of fractures in the alteration zones that were then infilled by not yet silicified carbonaceous sedimentary material overlying the silica caps, giving rise to the formation of carbonaceous chert dykes and veins. Ponding of hydrothermal fluids is indicated by the dramatic increase of chert veins immediately below sedimentary chert units (e.g., below the Buck Reef Chert). Breaching of the cap rocks, on the other hand, is evidenced by the occurrence of veins and dykes within, and the local brecciation of, the sedimentary chert horizons (e.g., at the top of the Kromberg Formation). The model presented here for the origin of the chert dykes is broadly similar to the one presented by Lowe and Byerly (1986). However, it emphasizes the importance of subseafloor hydrothermal processes, not only for the origin of the chert dykes, but also for the silicification of the overlying chert beds. Lowe (1999a), Knauth and Lowe (2003) and Tice and Lowe (2004) argued for a diagenetic origin of the early silicification, unrelated to hydrothermal activity.

Not all chert veins consist of carbonaceous sediment that was entrained into hydraulic fractures. Many veins consist of pure chert instead, and many of these show botryoidal features and cavity-filling megaquartz, suggesting that the chert precipitated out of hydrothermal fluids. Such veins are typically stratiform and are probably related to fluid overpressure. Fluid pressure must have exceeded the pressure from the overlying sediment and water column at times, which resulted in the opening of fractures oriented parallel to the seafloor. These fractures were then filled by hydrothermal chert and quartz. When breaching of the cap rocks took place, sedimentary material was able to become entrained in the stratiform veins locally. Because many stratiform botryoidal chert veins postdate carbonaceous chert dykes, this type of process took place relatively late in the evolution of the hydrothermal systems, possibly because of the increase in the thickness of the capping cherts with time. Many modern subaerial hydrothermal deposits are characterized by extensive breccia deposits which form during hydrothermal eruptions in active geothermal fields (Browne and Lawless, 2001). The complete absence of such deposits in the BGB may suggest that water depths during deposition of many sedimentary cherts were not as shallow as assumed by many authors (Lanier and Lowe, 1982; Lowe, 1999a).

Besides the filling of hydrothermal veins, a few carbonaceous chert veins formed differently. Some carbonaceous chert beds did not become lithified before being buried by overlying strata. Rapid burial or earthquake shock may have resulted in sediment fluidization and mobilization of carbon-bearing gelatinous silica to form cross-cutting veins, as observed in the upper part of H3c. Carbonaceous cherts of the Buck Reef Chert, that show soft-sediment deformation features, may have been affected by similar processes.

Not all of the silicification was associated with hydrothermal processes on and below the seafloor. Instead, a variety of rocks situated adjacent to the Granville Grove Fault became silicified too. This type of silicification is best ascribed to hydrothermal fluids that were channelled along the shear zone. Disturbing is that such rocks are compositionally very similar to the other chert types. This means that care needs to be taken when using chert horizons as stratigraphic marker horizons, because they may have formed in the vicinity of shear zones.

Carbonaceous matter in the dykes was probably derived from the overlying sedimentary horizons. This is supported by very similar petrographic characteristics as well as geochemical and isotopic data (Hofmann, unpubl. data). The origin of the kerogen is not known and a matter of much debate. Shales and turbiditic greywackes of the Fig Tree Group in the northern part of the belt contain carbonaceous matter in similar proportions to the cherts (Reimer, 1975); carbon isotope data are also similar and are indicative of biological fractionation processes (Hayes *et al.*, 1983; Walsh and Lowe, 1999; Hofmann, unpubl. data). Because mat-like carbon accumulations are rare, most of the carbonaceous matter probably settled out of the water column and may have originally formed in the shallow part of the Archaean ocean, possibly by modern pelagic organisms. Although the possibility that the carbon was derived from abiologically produced organics in the water column cannot be discounted, an organic origin appears far more plausible. Beside the ubiquitous kerogen clots and the more rare mat-like accumulations, secondary carbonaceous matter was observed in the pore space of carbonaceous chert at one locality (Fig. 6d). The origin of this material is not clear and it may represent the remains of degraded hydrocarbons.

This study highlights the importance of detailed field work prior to sampling of carbonaceous cherts for micropalaeontological or chemical analyses. Chert dykes are generally easy to distinguish from bedded sedimentary cherts, because of their cross-cutting geometry. Much more difficult to distinguish are stratiform veins in bedded chert host rocks, especially in areas of poor exposure. This is particularly difficult when they show layering, which can be very similar to sedimentary bedding. Furthermore, replacement of sedimentary rocks by chert is common in the vicinity of chert dykes. In addition, many translucent chert bands are secondary, and when present in stratified cherts, are very difficult to distinguish from primary chert precipitates.

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