7. DISCUSSION

This chapter combines the stress directions derived in Chapter 6, together with structural data obtained from the literature study presented in Chapter 5, and the tectonic history of the Kaapvaal Craton discussed in Chapter 4. The aim is to attain an understanding of the possible stress fields which existed in and around the Bushveld Complex region during different time periods. Attempts are made to construct a single stress ellipse which can accommodate the stress directions, as well as incorporate the orientations of all the various structures, of a specific age. By doing so it is possible to see if a single stress field prevailed during a specific time period, or if different stress fields existed during the proposed time bracket. Finally, regional tectonic events affecting the Kaapvaal Craton are used to provide possible explanations for the causes of these stress fields. However, due to the lack of detailed structural information about certain structures, different possibilities of stress ellipses are considered and alternatives regarding the timing and displacement style of such structures are discussed.

The time periods which are considered include, pre-Transvaal, syn-Transvaal, post-Transvaal/pre-Bushveld, post-Bushveld/pre-Waterberg, post-Waterberg/pre-Karoo, Pilanesberg and post-Karoo periods. Tables 7.1 – 7.4, summarize the regional tectonic events, local events, the stratigraphy of the Bushveld Complex area, and present the possible stress ellipses for each time period.

7.1 Pre-Transvaal

The pre-Transvaal time bracket stretches over a long time period during which the Kaapvaal Craton was subjected to many deformational events (e.g. McCourt, 1995). During this time variously orientated stress fields existed, causing basin formation and subsequent basin inversion. It is also evident that since the Craton's early evolution prominent structural grains developed which played an important role throughout the later history of the Craton. These structural grains are exemplified by greenstone belts as well as important lineaments such as the TML, Limpopo belt, and Barberton lineament. Prominent Archaean structural trends include ENE to NE as well as NNW orientated structures. Unfortunately, due to the lack of sufficient pre-Transvaal structures in the BOSGIS database, the stress fields which existed during this time are not well represented in this study. Only a few strike-slip faults

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namely the, Strydpoort, Ysterberg and Rietfontein faults, depict pre-Transvaal deformation in the study area. In addition, based on cross-cutting relationships, the NE-trending dykes developed in Archaean granites of the eastern Kaapvaal Craton might have formed during pre-Transvaal times.

A single stress ellipse (stress ellipse A, Table 7.1) can be constructed which accommodates left-lateral movement along the major faults (Charlesworth et al., 1986; de Wit and Roering, 1990; Potgieter, 1992), and the orientation of the dykes. It is therefore suggested that dyke formation and the strike-slip faults might have formed at the same time. However, it can be concluded that this single stress ellipse (Table 7.1) is an oversimplification of the stress fields existing during pre-Transvaal times in the Bushveld Complex area, but it can explain the ENE Archaean grain along which ancient crustal blocks accreted (de Wit et al., 1992; de Wit and Hart, 1993) and which controlled the formation of younger sedimentary basins.

7.2 Syn-Transvaal

The syn-Transvaal period can be grouped into three major stages, proto-basin development, post-Chuniespoort Group, and syn-Pretoria to post-Pretoria Group stage.

Eriksson et al. (1996) suggested that Transvaal proto-basin development was probably linked to strike-slip movement along the TML. The Ysterberg and Strydpoort faults have been interpreted as active growth faults during Wolkberg Group deposition (Potgieter, 1992). Stress directions derived for these faults indicate extension in a NNW-SSE direction (Figure 6.17 B). In a left-lateral strike-slip system, this NNW-SSE extension would have prevailed to accommodate movement along the Ysterberg and Strydpoort growth faults (stress ellipse A, Table 7.2). This ellipse is similar to the ellipse determined for the pre-Transvaal time period (stress ellipse A, Table 7.1), and therefore it can be concluded that Archaean stress fields influenced Transvaal proto-basin development.

Potgieter (1992) suggested that after deposition of the Chuniespoort Group, a major period of regional NNW-SSE directed compression resulted in the uplift of the Chuniespoort basin, causing a sedimentary hiatus of 150 Ma. This deformation resulted in the ENE trending folds of the Mhlapitsi fold belt as well as ENE trending strike-slip and thrust faults. Stress directions derived from these structures indicate a strong NNW compressional direction (Figure 6.25). However, no other evidence for this regional compression has been recorded in other parts of the Chuniespoort basin. It is therefore suggested that the deformation might have been linked to right-lateral movement along the TML as illustrated by stress ellipse B (Table 7.2).

The Pretoria basin is interpreted as a rift related basin (Schreiber et al., 1992) or as the result of half-grabens, controlled by the TML. During syn-Pretoria times, the Rustenburg fault displays normal movement (Bumby, 1997). Extension directed towards the NE could have accommodated this type of faulting (Figure 6.15 B). The Groot Marico and Swartruggens faults follow the same orientation as the Rustenburg fault, and therefore might also have been syn-Pretoria normal faults. If right-lateral movement along the TML prevailed during syn-Pretoria times, then stress ellipse B (Table 7.2) would remain valid, and can explain the Rustenburg fault developing as a secondary normal fault with in a large strike-slip system. On the other hand, stress ellipse C (Table 7.2) illustrates the orientation of the stress field if the Rustenburg fault developed as a primary normal fault, perhaps due to extensional stresses related to rifting.

It seems as if ongoing movement along the TML played a fundamental role during deposition and deformation of the Transvaal basin. In addition, the same directions (NE and NW) for extension and compression are constantly reutilized. These are the same directions which were established early on in the evolution of the Kaapvaal Craton.

7.3 Post-Transvaal/Pre-Bushveld

The post-Transvaal/pre-Bushveld time bracket is relatively short and no evidence of regional tectonic events of this age, except for the Eburnian orogeny along the SW margin of the Craton, have been documented (Thomas et al., 1993). Also, based on the constant strike-and-dip values of the Transvaal basin it appears as if the Transvaal basin was not subjected to any large scale regional deformational events. Yet, the presence of several large faults (Rustenburg, Wonderkop, Steelpoort and Laersdrif faults), as well as the interference fold patterns documented by Hartzer (1994) and Bumby (1997) need to be accounted for. Hartzer (1994) proposed two deformational events during post-Transvaal but pre-Bushveld times. The first period (D_1) implies compression towards the NE, while D_2 is characterized by a NW directed compression, possibly related to the Eburnian orogeny. Some workers (Potgieter, 1992; Du Plessis, 1990) proposed left-lateral movement along the TML during pre-Bushveld times.

Several large faults of post-Transvaal age are present in the Bushveld Complex and surrounding Transvaal rocks. These faults include the right-lateral Rustenburg (Bumby, 1997), normal Rietfontein (Charlsworth et al., 1986), left-lateral Wonderkop (Hartzer, 1994), right-lateral or normal Steelpoort (Visser, 1998; Sharpe and Snyman, 1980) and Laersdrif fault. In addition, the well documented interference fold patterns of the Transvaal Inliers (Hartzer, 1994) are also a characteristic feature of this time period. To accommodate these structures into one stress ellipse is a bit more problematic, partly due to a lack of geological information for most of the major faults. Therefore, several possible stress ellipses were considered.

The only stress ellipse which can accommodate the NW trending Rustenburg and NE trending Wonderkop fault into a single stress field is illustrated in stress ellipse D (Table 7.2). This would require a σ_1 directed NS, during which the Rustenburg and Wonderkop faults were conjugate strike-slip faults. This stress ellipse requires right-lateral movement along the Rustenburg fault and left-lateral movement along the Wonderkop fault. These faulting styles have been proposed for both faults (Hartzer, 1994; Bumby, 1997). However, this stress ellipse fails to explain the interference fold pattern observed in the Transvaal rocks observed by Hartzer (1994).

Stress ellipse E (Table 7.2) can accommodate folds with NW orientated fold axes, and normal faults orientated in a northeasterly direction as secondary structures related to a large ENE trending left-lateral strike-slip system. Hartzer (1994) and Bumby (1997) both recorded F_1 folds with NW trending fold axes in the Transvaal rocks, also, if the Wonderkop and Steelpoort faults were pre-Bushveld normal faults, then they might have formed under these stress conditions. However, if the Wonderkop fault was a pre-existing weakness, left-lateral movement along the fault could also have occurred under these stress conditions.

Stress ellipse F (Table 7.2) accommodate NE orientated fold axes, and NW orientated normal faults as secondary structures related to right-lateral movement in a large ENE strike-slip system. Large NE trending anticline and syncline pairs occur in the western Transvaal basin, but no documentation of NW orientated post-Transvaal normal faults exist. However, according to Bumby (1997) extensive right-lateral displacement along the pre-existing Rustenburg fault, could have occurred under these stresses (ellipse F Table 7.2).

The last set of structures that needs to conform to the stress fields active during post-Transvaal times, are the radial faults around the Johannesburg dome. These faults might be due to post-Transvaal uplift of the dome (Allsop, 1961) which would have resulted in only a localized stress field. However, the uplift might be due to post-Transvaal normal movement along the Rietfontein fault (Charlsworth et al., 1986). The Rietfontein fault trends NE and would therefore fit well into stress ellipse E (Table 7.2).

It is almost impossible to attribute a single stress field to the different orientations and styles of the various faults. The proposed stress fields can only be accurate if structures formed as secondary structures resulting from a major strike-slip system. Such a strike-slip system might have existed between the TML and the Barberton lineament. Prolonged left-lateral (D_1) and right-lateral (D_2) movement within this strike-slip zone would have been the cause of the opposing stress directions observed during this time. If this supposed lateral movement can be ascribed to the Eburnian orogeny remains speculative. However, it might also be possible that only localized stress fields deformed the Transvaal basin during pre-Bushveld times. Stresses might have been imposed by the updoming of the Bushveld Complex, and therefore intense deformation do not extend across the entire Transvaal basin. However, Bumby (1997) argues that most of the stress imposed by the Eburnian orgogeny was accommodated by the Rustenburg fault and therefore no large scale deformation is present further towards the east.

7.4 Post-Bushveld/Pre-Waterberg

The poorly documented structures present in the Bushveld Complex contributes to the uncertainty about the tectonic setting of this large layered intrusion. Opinions vary greatly (see Chapter 4.2) from an active tectonic environment in which rifting allowed for the intrusion of such a large igneous body to a stable cratonic setting into which a rising mantle diapir was responsible for the emplacement of the Bushveld Complex. Du Plessis and Walraven (1990) suggested left-lateral movement along the TML during and after the emplacement of the Bushveld Complex. On the other hand, some workers (Uken and Watkeys, 1997b) believe that EW compression and NS extension prevailed during the intrusion of the Bushveld Complex. In contrast, Van Biljon (1976) suggested EW extension during the emplacement of the Complex. Not enough structural information is available to constrain the stress conditions existing during syn-Bushveld times.

EW compression (Uken and Watkeys, 1997b) would result in stress fields illustrated by stress ellipse G (Table 7.2). These directions could explain the large EW striking lineaments present in the western Transvaal basin. However, EW compression (van Biljon, 1976) would result in opposite stress fields (ellipse K, Table 7.2) and can possibly explain the NS trend of the northern lobe of the Bushveld Complex.

Understanding the stress fields which existed during post-Bushveld times are just as problematic as the pre-Bushveld and syn-Bushveld stress fields. Again, this is due to the poorly constrained ages and faulting styles for the Wonderkop, Brits Graben, Steelpoort and Laersdrif faults. Based on cross-cutting relationships, these faults may have a minimum age of post-Karoo. However, in this study these faults are considered as at least pre-Waterberg in age. The Rustenburg fault is not considered as a post-Bushveld fault since Bumby (1997) suggested that the pre-existing Rustenburg fault did not reactivate during Bushveld times since recrystalization of the fault zone during the intrusion of the Bushveld Complex caused the fault zone to be more competent than the host rock. It appears however, as if the eastern compartment of the Complex is dominated by NE orientated faults (Steelpoort, Wonderkop faults), whereas the western compartment is dominated by NW trending faults (Brits Graben, Crocodile River faults). Other prominent structures which need to conform to the stress fields of post-Bushveld times are the large NW orientated folds observed in the granites of both compartments (Walraven, 1974; Walraven, 1986). The following question thus arises: was the Bushveld Complex subjected to opposing stress fields of the same age, or did two separate stress fields of different ages affect the Complex?

Stress conditions as illustrated by stress ellipse G (Table 7.2) and would explain normal movement of the NE orientated Wonderkop, and Steelpoort faults, as well as the NW orientated folds observed in the Bushveld granites of both compartments. The sinuous nature of these folds might indicate syn-Bushveld folding when magma was still unsolidified and the fold axes probably rotated. Investigations by Tyler and Tyler (1996) in the marginal rocks of the eastern Bushveld Complex confirms ENE orientated compression during syn-Bushveld times.

Normal movement along the Crocodile River fault and Brits Graben (Hartzer, 1994; Visser, 1998) are not reconcilable with the proposed left-lateral movement along the TML, or EW extension or compression. Therefore, two separate stress fields are proposed to have existed in the eastern and western compartments. They are portrayed by stress ellipse I (western lobe) and J (eastern lobe) (Table 7.2) which implies NE and NW extension respectively. However, the proposed stress fields existing in the eastern compartment still fails to explain the orientation of the Laersdrif fault. A possible explanation might be that the fault is not post-Bushveld in age.

Stress analysis of this time period, suggests that at least two different stress fields must have existed during post-Bushveld times. It is possible that left-lateral movement along the TML existed during syn-Bushveld times till shortly after (ellipse H, Table 7.2). The stress fields as illustrated by ellipses I and J then existed simultaneously after the left-lateral movement of the TML.. A possible cause for these opposing stress fields existing of the same time, might be due to locally induced stresses during thermal collapse of the Bushveld Complex (Visser, 1998). Therefore, similarly to the Transvaal basin, it appears as if the deformation of the Bushveld Complex was not the result of regional scale tectonic events, but was deformed by locally induced stress fields. Also, the strikingly similar strike-and-dip pattern of the Transvaal basin and Bushveld Complex, points to the fact that both sequences must have been subjected to similar regional tectonic events.

7.5 Post-Waterberg/Pre-Karoo

The post-Waterberg/pre-Karoo period has a very long time span (1800Ma – 350Ma). The absence of preserved sedimentary sequences during this time makes it difficult to place a more narrow time constraint on the deformational events affecting the Bushveld Complex and surrounding areas. In addition, no evidence exists for major tectonic processes affecting the Kaapvaal Craton during this time. The Waterberg basin is believed to formed in a half-graben setting with the TML marking the southern boundary (Callaghan et al., 1991). Du Plessis (1990) suggested left-lateral movement along the TML during proto-basin development. In addition tensional conditions existed on the Kaapvaal Craton due to cooling of the crust after the intrusion of the Bushveld Complex (Jansen, 1982). Two main theories exist regarding the deformation of the Waterberg basin, one favouring strike-slip movement (Du Plessis, 1990) and the other favouring mostly thrust movement

(Jansen, 1982) along the southern margin of the Waterberg basin. Stress interpretations of post-Waterberg times rely much on the geological evidence observed in the Waterberg rocks along the Thabazimbi-belt, which include EW orientated faults and folds. The smaller Cullinan-Middelburg basin is also characterized by EW striking faults. Other structures of the large Waterberg basin include some NW orientated faults and lineaments (Figure 6.8 C).

Du Plessis (1990) interpreted the large EW striking faults as strike-slip faults caused by post-Waterberg left-lateral movement along the TML. Stress ellipse A (Table 7.3) illustrates the possible stress field existing during this time. The complex interplay of faults was interpreted by Du Plessis (1990) as conjugate shears bounding flower structures. In addition, left-lateral movement along the Melinda fault during post-Waterberg but pre-Karoo times (Brandl and Reimold, 1990) fits well into this model/scenario.

However, the many EW orientated anticlines and synclines, and thrust faults along the southern margin of the Waterberg basin are not accommodated by stress ellipse A (Table 7.3). These folds show strong evidence for NS directed compression during post-Waterberg times (Jansen, 1982). Stress ellipse B (Table 7.3) illustrates the possible stress fields and the related structures. This stress field could have caused left-lateral reactivation along the TML as observed by Du Plessis (1990).

The final post-Waterberg deformation is marked by NE directed tension, exemplified by the Vaalwater and Boschpoort normal faults (Jansen, 1982). Stress ellipse C (Table 7.3) accounts for the structures formed due to these stress directions. The NW trending post-Waterberg lineaments are also reconcilable with these tensional conditions.

It is noteworthy that the previously constantly NE and NW directed stresses prevailing since pre-Transvaal times, change to NS and EW during post-Waterberg times. However, the regional tectonic event responsible for this NS compression remains enigmatic. The approximately 1000Ma Kibaran orogeny, marking collision along the SW and SE margins of the Kaapvaal Craton, can be a possible cause.

7.6 Pilanesberg

The intrusion of alkaline complexes is a characteristical feature during 1400Ma to 1300Ma. These complexes might have been structurally controlled by a NNE trending lineament (Figure 4.9) (Verwoerd, 1993). However, active post-Karoo structures, such as the Melinda fault and Zebediela fault, cut across this supposed lineament. Therefore, due to offsets caused by younger structures, the lineament observed today might not have been a lineament during Pilanesberg times.

The stress directions for the Pilanesberg times are solely derived from the Bos2 area, in which syenite dykes trend NW and the circular Pilanesberg Complex intruded along the western margin of the Rustenburg Layered Suite.

Syenite dykes indicate a NE orientated extensional stress field. This stress field would be similar to the stress ellipse C (Table 7.3) of late post-Waterberg times, and therefore it is possible that post-Waterberg stress conditions prevailed during the intrusion of syenite dykes.

The intrusion of the Pilanesberg Complex resulted in a localized circular stress field (stress ellipse D Table 7.3). However, σ_1 remains vertical during the intrusion, similar to stress ellipse C, and therefore the regional stress field could have been similar as during syenite dyke intrusion.

7.7 Post-Karoo

Reactivated post-Karoo normal faults, such as the Zebediela and Melinda faults, are probably responsible for Karoo rocks being preserved on the northern Kaapvaal Craton. The NE trending Olifants River dyke swarm (Uken and Watkeys, 1997a) is also a prominent extensional feature of this time period.

A single stress ellipse (ellipse A Table 7.4) can accommodate the orientation of the dyke swarm as well as the post-Karoo normal faults. The noticeable deflection in the orientation of the Olifants River dyke swarm in the Transvaal rocks versus the adjacent Archaean rocks (Figure 6.5 B and C) should not change the orientation of the proposed stress field. If the dykes in the adjacent Archaean granites are planes of pre-existing weaknesses of Archaean age (see 7.1) then they too would have been reutilized under this stress field. However, they might not be Archaean in age but simply have a slightly different orientation to dykes in the Transvaal rocks due to competency differences of the host rock.

A different set of dolerite dykes, trending NW, occur in the western Bushveld Complex area (Figure 6.3). The age of these dykes are unknown and they might be related to the post-Bushveld extensional period (stress ellipse H, Table 7.2). However, if these dykes are post-Karoo in age, they do not conform to stress ellipse A (Table 7.4), and therefore probably reflect a another opposing extensional stress field existing during post-Karoo times.

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Table 7.1. The Randian and Swazian periods (for discussion of stress ellipse see text)

Erathem	Age	Regional Events	Specific events	Intrusions	Formation	Stress ellipse
Randian	2.6			Various Granites	Amalia Kraaipan - greenstone belt	see figure
	2.65	Limpopo orogeny	Intra-cratonic tectonics - development of basins with ENE strike, continental growth along western and northern margin			
	2.687				Ventersdorp basin	
	2.7					
	2.8	Development of the Kaapvaal Craton - mosaic of crustal blocks accreted along large-scale ENE-striking shear zones.		Various Granites- Northern and western Kaapvaal Craton	Pietersburg greenstone belt	
Swazian	2.9				Witwatersrand basin	
	3				Murchison greenstone belt	
	3.1		Southern and central parts coherent unit - start of TML	Various Granites - eastern and southern Kaapvaal Craton Johannesburg dome	Dominion basin Pongola basin	
	3.2		Intra-oceanic tectonics - greenstones and granitization		Barberton greenstone belt	
	3.3					
	3.4					

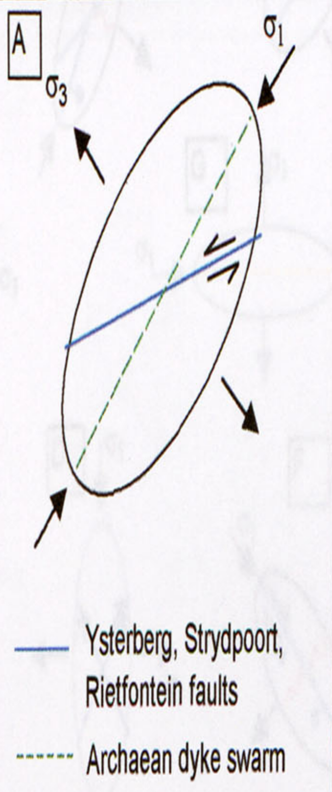

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Table 7.2. The Vaalian period (for discussion of stress ellipses, see text)

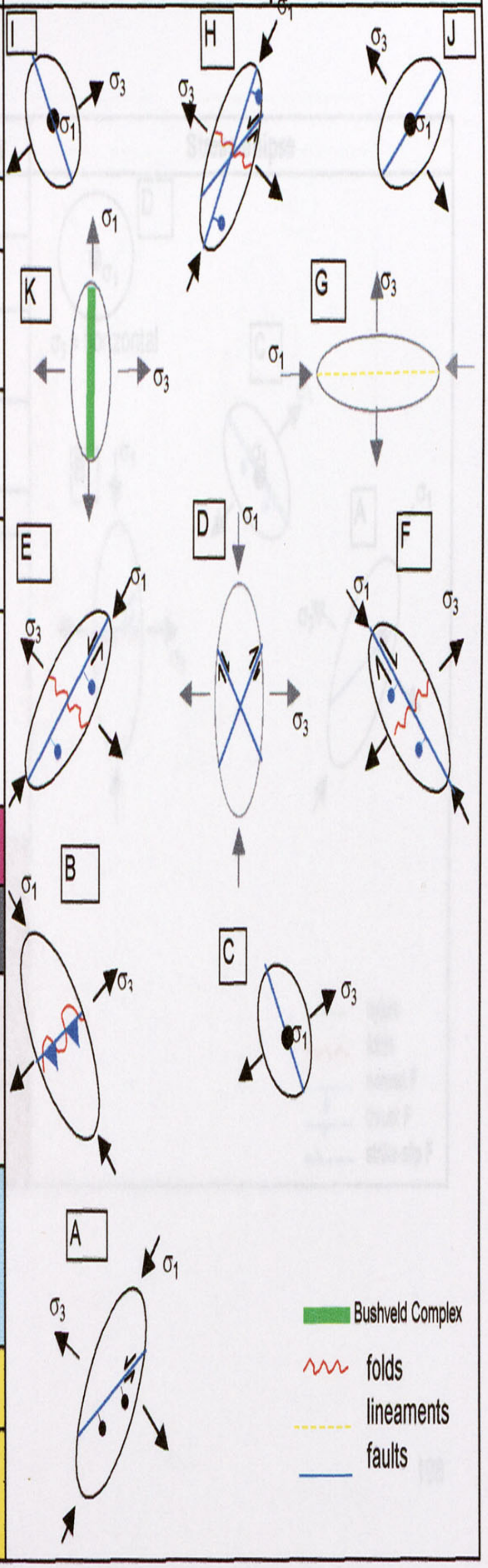
Erathem	Age	Regional events	Specific events	Intrusions	Formation	Stress ellipse
VAALIAN			Thermal collapse			
	2.02	Vredefort Dome				
	2.05	Left-lateral movement along TML	Intrusion of the Bushveld Complex	Lebowa Granite Suite		
	2.06			Rustenbug Layered Suite		
			Pre-Bushveld diabase intrusions - updoming	sills/dykes		
	2	Eburnian orogeny, plate-collision at the SW margin of Kaapvaal Craton	Folding of Transvaal rocks, D_1 (NW trending folds) D_2 (NE trending folds)			
	2.15		Volcanic activity		Rooiberg (felsite)	
	2.25	Half-graben - controlled by TML	Fluvial sedimentation. Rifting/Thermal subsidence		Pretoria	
	2.3	Regional NNW-SSE compresional tectonics	Uplift of Chuniespoort basin - sedimentary hiatus		Unconformity	
	2.4	Widespread Transvaal basin development - thermal subsidence, initially WNW axial trend	Minor periodical regional compression – Shallow eperic sea		Chuniespoort	
	2.6					
	2.67		Shallow sea		Black Reef	
		Transvaal proto-basin,	Strike-slip along TML, NNW-SSE extensional tectonics, active growth faults		Wolkberg	

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Table 7.3. The Mogolian period (for discussion of stress ellipses, see text)

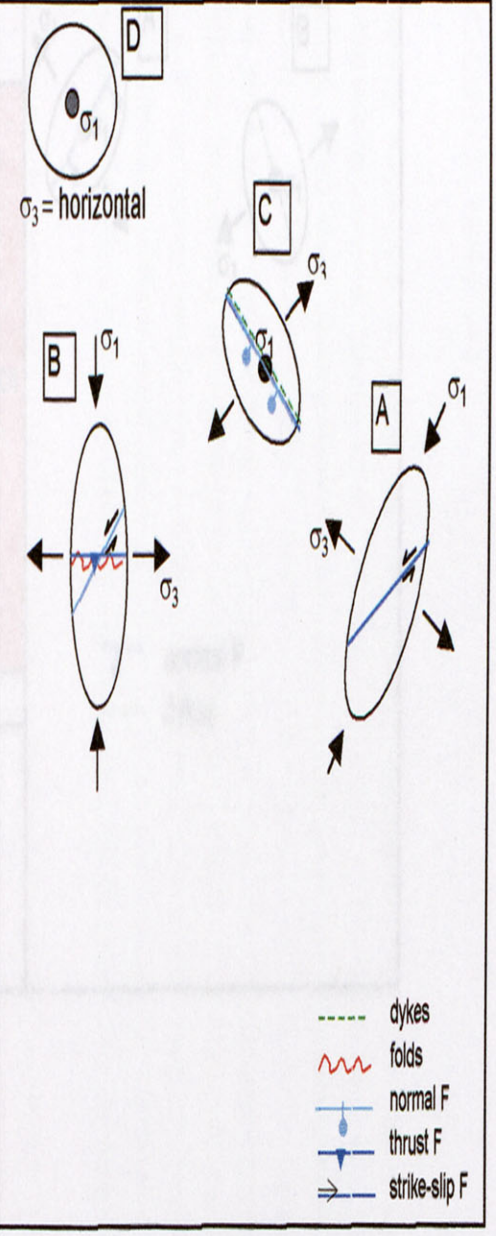
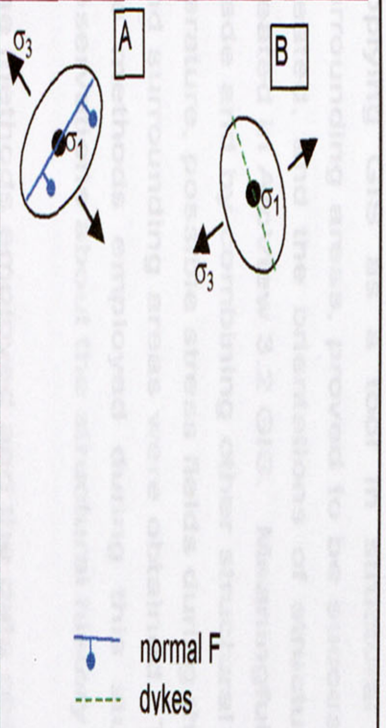
Erathem	Age	Regional Events	Specific events	Intrusions	Stratigraphy	Stress ellipse
Mogolian	1	Kibaran orogeny - Natal-Namaqua structural and metamorphic province				
	1.2					
	1.3	Intrusion of alkaline complexes		Pilanesberg		
	1.4			Spitskop		
			Tensional faulting	Diabase		
			Large scale NS compression			
	1.5	Deposition of Waterberg Group	Fluvial enviornment (alluvial fans, lakes, local deserts)		Waterberg	
	1.6					
	1.7		Block faulting			
	1.8	Nylstroom proto-basin and Alma trough, developed along TML				

Table 7.4. Karoo period (for discussion of stress ellipses, see text).

Erathem	Age	Regional Events	Specific events	Intrusions	Formation	Stress ellipse
Cenozoic	65	Epeirogenetic - Sea-level fluctuations				
Mesozoic	135	separation of west Gondwana (South America)	tension in Limpopo belt	Mesozoic dyke swarm	Karoo Sequnce	
	150	separation of east Gondwana (Antartica)		Karoo dolerites		
	190					
	200			Mesozoic dyke swarm		
	245	Cape orogeny				
Palaeozoic	280	Gondwana super continent	Formation of Karoo basin - rifting			
	300					
	400					
	500	Pan African orogeny - continental rifting				
	600					
	700					
	800					
	900					