THE HYDROGEOLOGY OF DOLOMITIC FORMATIONS IN THE SOUTHERN AND WESTERN TRANSVAAL

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Introduction

The most significant occurrence of carbonate rocks in the Republic of South Africa is the dolomitic strata of early Proterozoic age. The chronostratigraphically equivalent Chuniespoort and Ghaap Groups outcrop over an area of about 29 000 km^2 in the Transvaal and Northern Cape (see figure 1), and attain maximum thicknesses of 1880 and 1600m respectively. From isotopic dating of intrusive rocks in units above and below the Chuniespoort Group, the age of these sediments has been put at about 2300 Ma (Mac Gregor et al 1974). In this paper attention will be focussed only on the south-central and western Transvaal.

This region contains the highly populated and industrialised Pretoria-Witwatersrand-Vereeniging (PWV) area, the important gold mines of the Far West Rand and the extensive agricultural plains of the Western Transvaal. Its general geology is well known largely as a result of the exploration for gold. Hydrogeology and engineering geology have also received more attention here than elsewhere, as a result of the problems associated with man's interference in the hydrologic environment of this carbonate region.

Considerable problems have been encountered in the gold mines of the Far West Rand as a result of very large ground water inflows where the dolomitic formations overlie the gold-bearing strata of the Witwatersrand Supergroup. Dewatering of dolomite aquifers by the mines resulted in unprecedented ground subsidence and sinkhole formation. Associated with this, considerable effort has been spent conducting gravity surveys, and drilling programmes in order to

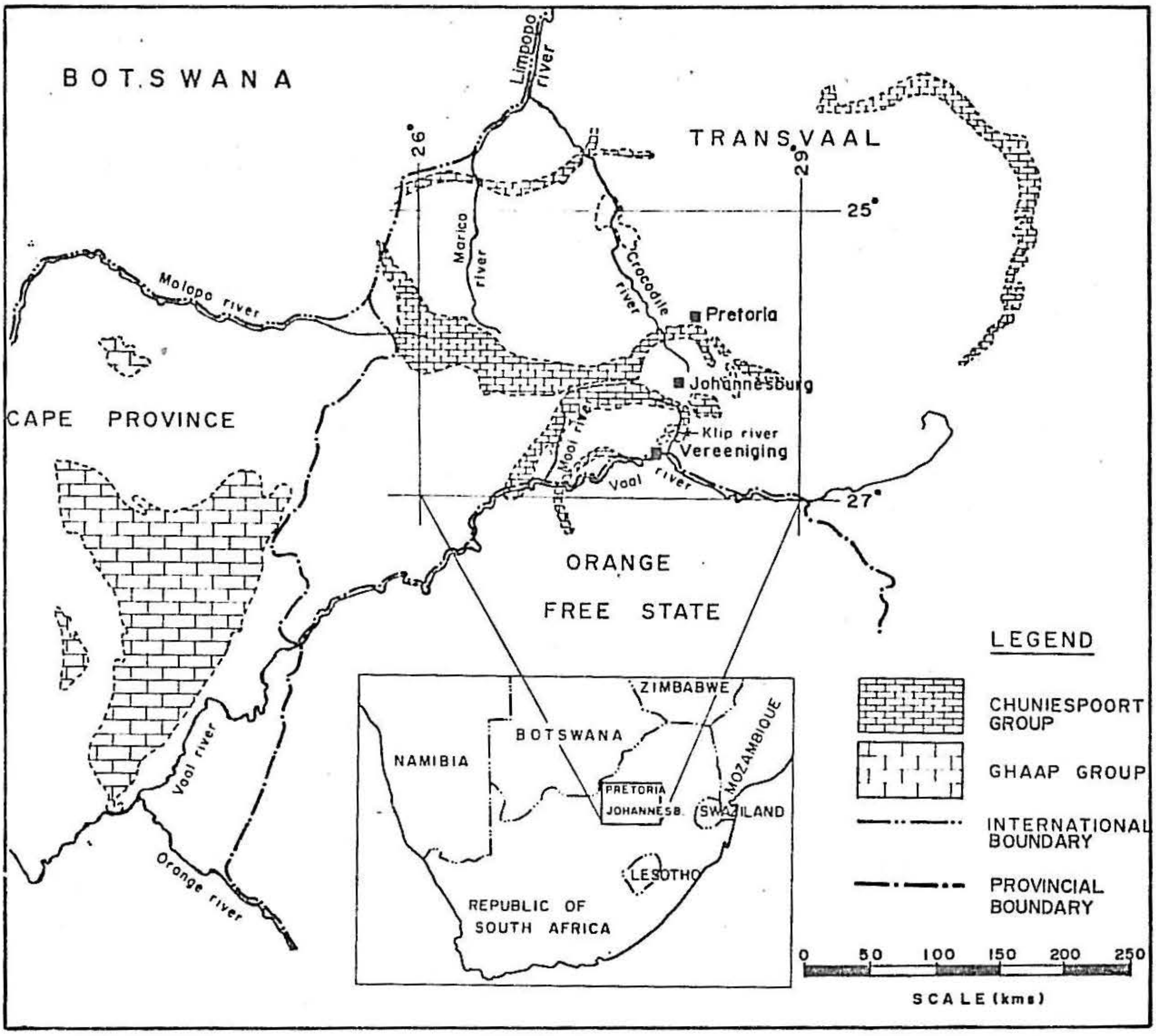


FIGURE 1. Distribution of Proterozoic dolomitic strata in the Northern Cape and Transvaal

delineate potentially unstable ground (Kleywegt and Pike, 1982). Rapid urbanisation similarly requires investigations into ground stability, liquid and solid waste disposal and pollution control.

Recent detailed hydrogeological investigations, including geophysical surveys and exploratory drilling have contributed much to knowledge of this terrain. They were conducted in order to assess and develop the dolomitic ground water resources for emergency supplies to the metropolitan PWV area in a period of prolonged drought and critically low dam levels.

The area under description (see figures 1 and 2) is situated on the Highveld which forms part of the country's interior plateau. It extends over the watershed between the northward draining tributaries of the Limpopo River and the southward flowing tributaries of the Vaal River. Headwaters of the Molopo flow to the west. The surface elevation varies from 1750m at Johannesburg and 1400m at Potchefstroom to 1460m at Lichtenburg. The climate is warm temperate with summer convectional rainfall varying across the area between a mean of 640mm in the west to 730mm in the east. Annual potential evaporation varies between 1400mm and 1800mm.

Geology

General

The dolomitic formations of the Chuniespoort Group were deposited in a vast epeiric basin on the Kaap-Vaal craton, one of the oldest blocks on the African plate. They form part of a 12 000m thick succession of clastic and chemical sediments and volcanic rocks of the Transvaal Sequence. The Chuniespoort Group attains a thickness of 1200 metres on the Far West Rand (Cousins 1962) and near Bapsfontein a thickness of 1000m has been recorded (Button 1969).

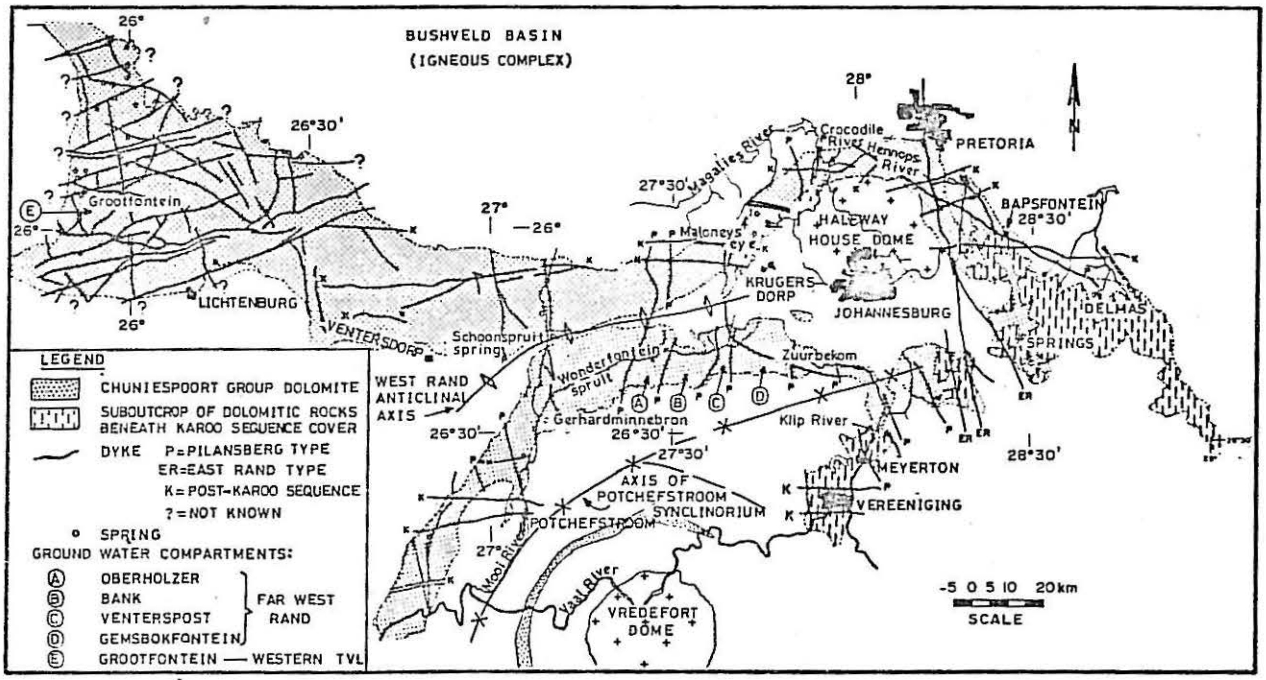


FIGURE 2. Dykes and ground water compartments in south-central and western Transvaal

Lithostratigraphy

Excluding the extreme far west where ironstones make their appearance at the top of the succession, the Chuniespoort Group in south-central and western Transvaal comprises four lithostratigraphic Formations (figure 3). The Formations are distinguished on the basis of their chert content. Owing to poor exposure the recognition and mapping of the different Formations presents considerable difficulties in places.

Two main types of lithology are present:

(i) chert-free micritic or recrystallised dolomite

(ii) chert-rich dolomite composed of alternating beds, bands and laminae of chert and dolomite.

Geochemistry

Samples of drill cuttings taken at one metre intervals from five boreholes penetrating different stratigraphic horizons in the Bapsfontein area have been analysed using X-ray fluorescence. The CaO content of the rock was found to vary from about 10 to 35 percent and the MgO content from about 8 to 21 percent. SiO_2 content ranged from less than 1 to over 60 percent in chert-rich zones. The variation in ionic Ca:Mg ratio is shown in figure 4. In 84,5 percent of the samples the Ca:Mg ratio exceeds the theoretical value for pure dolomite. (Ionic Ca:Mg ratio of 1:1 equivalent to a 1:0,72 ratio by weight of CaO:MgO).

System / Erathem	SEQUENCE	GROUP	FORMATION		LITHOLOGY AND MEMBER	Thickness (m)
PERMO-CARBONIFEROUS	KAROO	ECCA			Sandstone Mudstone Carbonaceous shale, coal	
			Dwyka		Diamictite	
PROTEROZOIC	TRANSVAAL	PRETORIA	Timeball Hill		Shale Diamictite Klapperkop Quartzite Mb wacke and ferruginous quartzite. Graphitic and silty shale	270-660
			Rooihoogte		Quartzite Shale Bevets Conglomerate Member Breccia	10-150
		CHUNIESPOORT	Eccles		Chert-rich dolomite with large and small stromatolites	380
			Lyttelton		Dark chert-free dolomite with large elongated stromatolitic mounds	150
			Monte Christo		Light coloured recrystallised dolomite with abundant chert; stromatolitic; basal part oolitic	700
			Oaktree		Dolomite, becoming darker upwards. Chocolate-coloured weathering	200
			Black Reef Quartzite		Shale Quartzite Arkosic grit	25-30

FIGURE 3. Partial stratigraphic column showing only strata directly underlying or overlying the Chuniespoort Group (after SACS 1980 fig. 4.1.4.)

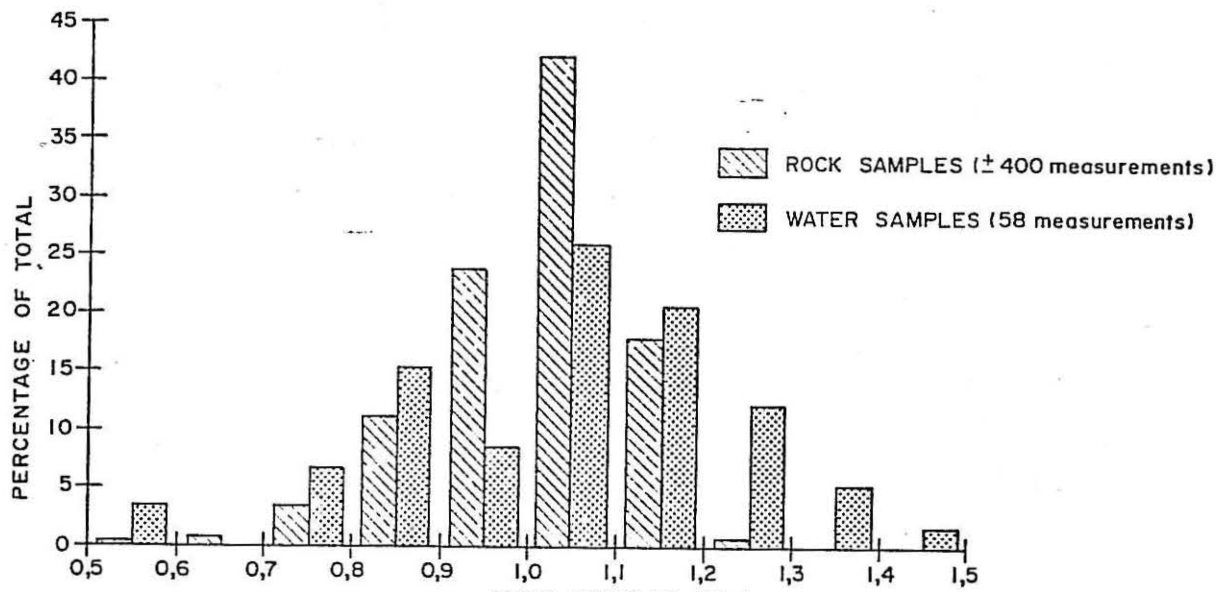


FIGURE 4. Histogram of Ca/Mg ionic ratios for Chuniespoort Group rocks and uncontaminated dolomitic ground water in the Bapsfontein area.

Roux (1981) found that south of Pretoria the FeO content varies from less than 0,1 to 6,1 percent and MnO ranges from about 0,2 to 3,7 percent. The FeO:MnO ratio of 44 samples averages 0,9; the range in values is 0,2 to 1,85. Small amounts of Ba, Co, Sr, V and Sn in the order of several parts per 100 000 are also present. It is believed that these chemical data are more or less representative of the whole area under discussion.

Sedimentology and diagenesis

Algal sedimentary features are widely developed in all the Formations. Detailed studies of the stromatolite morphology have indicated that lithological variation is a response to different depositional environments (Eriksson and Truswell 1974).

The chert-rich Monte Christo and Eccles Formations are characterised by oölites, lamination and ripple marks as well as columnar and domal stromatolites with a maximum relief of 1 metre. These features are diagnostic of an intertidal to supratidal environment comparable to the modern examples of Shark Bay, Western Australia (Logan et al 1964) and the tidal and fresh water marshes of the Everglades, Florida (Monty and Hardie 1976).

Large elongate domal stromatolites of the chert-poor Oaktree and Lyttelton Formations are up to 16m long and 3m in relief. The only known stromatolite forms growing today comparable in size, occur in the subtidal environment of the Eastern Bahama Bank (Dill et al 1986).

The presence of chert has been explained by Foster (1988b) to result from different diagenesis in the two contrasting depositional environments. The original carbonate sediments of the chert-poor formations were dolomitised in a migrating schizohaline environment (seawater-freshwater mixing zone) during basin subsidence and shoreline transgression. The interbedded dolomite and chert of the Monte Christo and Eccles Formations may be the result of two possible modes of diagenesis depending upon the thickness of the chert and dolomite beds. Applying the theories of Badiozamani (1973) and Knauth (1979) the formation of the thicker beds may be explained by alternate dolomitization and silicification of the primary carbonate sediments in a seawater-freshwater mixing zone during minor cyclical marine transgressions and regressions. The very fine dolomite and chert interlamination can not however be explained by this process. It is more likely that silicification occurred in response to a pH change resulting from the periodic flooding of an area of freshwater carbonate marshes, mud flats and tidal deltas. The additional possibility of evaporative dolomitisation acting in this environment is not ruled out.

Three unconformities marked by angular chert fragments in a shale matrix and overlain by thin shale beds have been identified in the carbonate succession (Eriksson and Truswell 1974). A regional angular unconformity also marked by a chert-shale breccia separates the Chuniespoort and overlying Pretoria Groups. The chert breccias represent insoluble residues of carbonate dissolution on subaerial erosion surfaces.

Structural geology

The major structural features in the southern and western Transvaal originate from the period of upheaval and igneous intrusion (between approximately 2100 Ma and 1700 Ma) which followed the deposition of the Transvaal Sequence.

A full description of this complex period of tectonism and igneous intrusion is beyond the scope of this paper but the main features are the Transvaal basin intruded by the Bushveld Complex, the West Rand anticline, the Halfway House and Vredefort granitic domes, and the Potchefstroom synclinorium (see figure 2).

Except for the narrow band of steeply dipping and overturned dolomitic strata which encircle the Vredefort dome and which have not been studied hydrogeologically, rocks of the Chuniespoort Group have in general not undergone intense deformation. Dips are for the most part low to moderate and folding is generally gentle. Owing to the poor exposure of the Chuniespoort Group, faulting is best observed in the immediately overlying and underlying units. Normal, wrench, reverse and thrust faults have been mapped in various parts and are evident in the published 1:250 000 geological sheets (Geological Survey of South Africa 1986, nos. 2526, 2528, 2626, 2628).

Intrusives

One of the most characteristic features of the regional geology is its network of intersecting dykes (figure 2). There were at least three main episodes of dyke emplacement (Day 1980): Pilanesberg (1310 ± 60 Ma), East Rand (1120 ± 65 Ma) and post-Karoo Sequence age (150 to 190 Ma). In addition the Chuniespoort Group strata have been intruded by sills possibly associated with intrusion of the mafic layered suite of the Bushveld Complex (2096 Ma) as well as sills of post-Karoo age.

Post-Transvaal sediments

After the early Proterozoic, the area was subjected to an extended period of erosion (including Carboniferous glaciation on a continental scale) and no evidence of sedimentation between the Transvaal and Karoo Sequences remains in this area. Only lower basin-margin Karoo sediments are present. These consist of diamictite, where present in deeply eroded channels, followed by glaciolacustrine and glaciofluvial deposits of the Dwyka Formation of late Carboniferous - early Permian age, in turn followed by shales, mudstones, sandstones and coal beds of the Vryheid Formation of the Ecca Group.

The extensive tracts of tranported soils from the Tertiary to Recent times are largely hillwash deposits derived from the chert and quartzite ridges of the Rooihoogte and Timeball Hill Formations. They comprise coarse chert debris and red sands, the latter being widespread and possibly redistributed by wind during an arid climatic period (Brink 1985).

Karst

Dissolution process of dolomitic rock

Martini and Kavalieris (1976) recognise three distinct successive stages of dissolution of dolomite corresponding to three zones of rotten rock with a total thickness of about 10cm.

The incipient stage is evident as intergranular staining of carbonate crystals by oxides of iron and manganese with depletion of Ca and Mg at crystal boundaries. Although dissolution is strongly selective along crystal boundaries, microprobe analysis of fresh dolomite shows no primary variation in composition across crystal boundaries.

In the further stage of dissolution, the dolomite is characteristically granular and is easily crushed. Carbonate crystals show a heavy oxide coating. Quantitative analysis for Ca and Mg of fresh and weathered dolomite reveal that the Ca/Mg ratio remains unchanged during dissolution.

In the final stage of dissolution which is only preserved in protected environments, all the carbonate is removed and a cellular fabric composed of iron and manganese oxides and hydroxides and silica, pseudomorphing the original crystal structure remains. This is a highly erodible and compressible soil locally termed 'wad'.

History of karst development

Although erosion during successive periods has progressively removed traces over the greater part of the dolomitic strata, there is evidence of at least four periods of karstification according to Martini and Kavalieris (1976):

(i) Pre-Pretoria period (about 2250 Ma) - Evidence for a period of karstification before the deposition of the Pretoria Group is widely represented by a chert breccia with dark siliceous matrix developed on top of the carbonate sequence. In the far western Transvaal Martini (1975) has described karst features that developed in this period. These features consist of palaeosinkholes and cave passages filled with residuals now represented by black siliceous shale, rich in carbon inherited from the dolomite, collapsed chambers and breccia bodies. In places mineralisation with fluorspar, lead and zinc has taken place. The unconformities within the Chuniespoort Group may also be considered palaeokarst horizons.

(ii) Pre-Waterberg period (about 1700 Ma) - Outside the area under consideration, red sandstone correlated with Waterberg Group rocks has been observed infilling dissolution cavities.

(iii) Pre-Karoo period - This erosion period of about 1300 million years was terminated by the development of the continental Carboniferous ice shield.

Drilling for geotechnical purposes, coal mining and exploration for refractory clay deposits (Wilkins et al 1987; Cillie 1961; Bredell 1987 etc.) have repeatedly demonstrated that Karoo strata were deposited on an undulating karst palaeotopography. Although it has been suggested by certain workers (e.g. Marker 1974) that outliers of Karoo sediments owe their existence to collapse into karst depressions when the Karoo cover was being eroded, evidence provided by Bredell (1987) and Wilkins et al (1987) demonstrates that primary sedimentation processes formed the succession in the Karoo outliers. Localized dips and small scale folds along the edges of outliers and a thickening of higher-lying beds over filled-up floor depressions point to continued subsidence during sedimentation. Subsidence may have been caused either by karstic collapse or by dewatering and compaction.

(iv) Post-Karoo period - Tertiary to Recent.

Episodic uplift of much of South Africa commenced during fragmentation of Gondwanaland in the late Mesozoic and was followed by further uplift in late Tertiary. This led to renewed exposure of the Chuniespoort Group and evolution of a karst landscape. Evidence for post-Karoo karst formation is provided by sinkholes and dolines near Pretoria in which clayey and sandy silt have been deposited on top of Karoo infilling. On the Far West Rand palaeosinkholes have been infilled by red aeolian sand and fluvial gravel, sand and clay. The red sand is considered to be representative of Tertiary aeolian sand deposits which cover extensive areas of southern Africa.

Geomorphology

With the exception of the dissected northwestern flank of the Halfway House Dome the dolomitic strata typically occupy flat featureless terrain or wide shallow valleys. The strata are largely obscured by patches of Karoo Sequence (only partially shown in figure 2) or the more extensive Tertiary to Recent deposits. Higher ground is normally occupied by chert ridges. The lowest quartzite of the overlying Pretoria Group commonly forms an escarpment rising up to 100m above the Chuniespoort Group outcrop (figure 15).

Three karst morphological types have been identified in south-central and western Transvaal by Martini and Kavalieris (1976). The distribution of the types is shown in figure 5.

(i) The Plateau type - This is the most extensive morphological type and occupies the flat plateau between Krugersdorp and the Botswana border. The Plateau type has few surface streams and those flowing from bounding formations disappear upon entering the dolomitic terrain. From these points of disappearance dry stream courses may extend several kilometres further on the dolomite. Spring flows rising from the dolomite likewise disappear underground. In the western Transvaal several large polje-like depressions occur. They are not generally associated with water caves as in the classic poljes of Yugoslavia but drain into sediment-choked dissolution features at their margins.

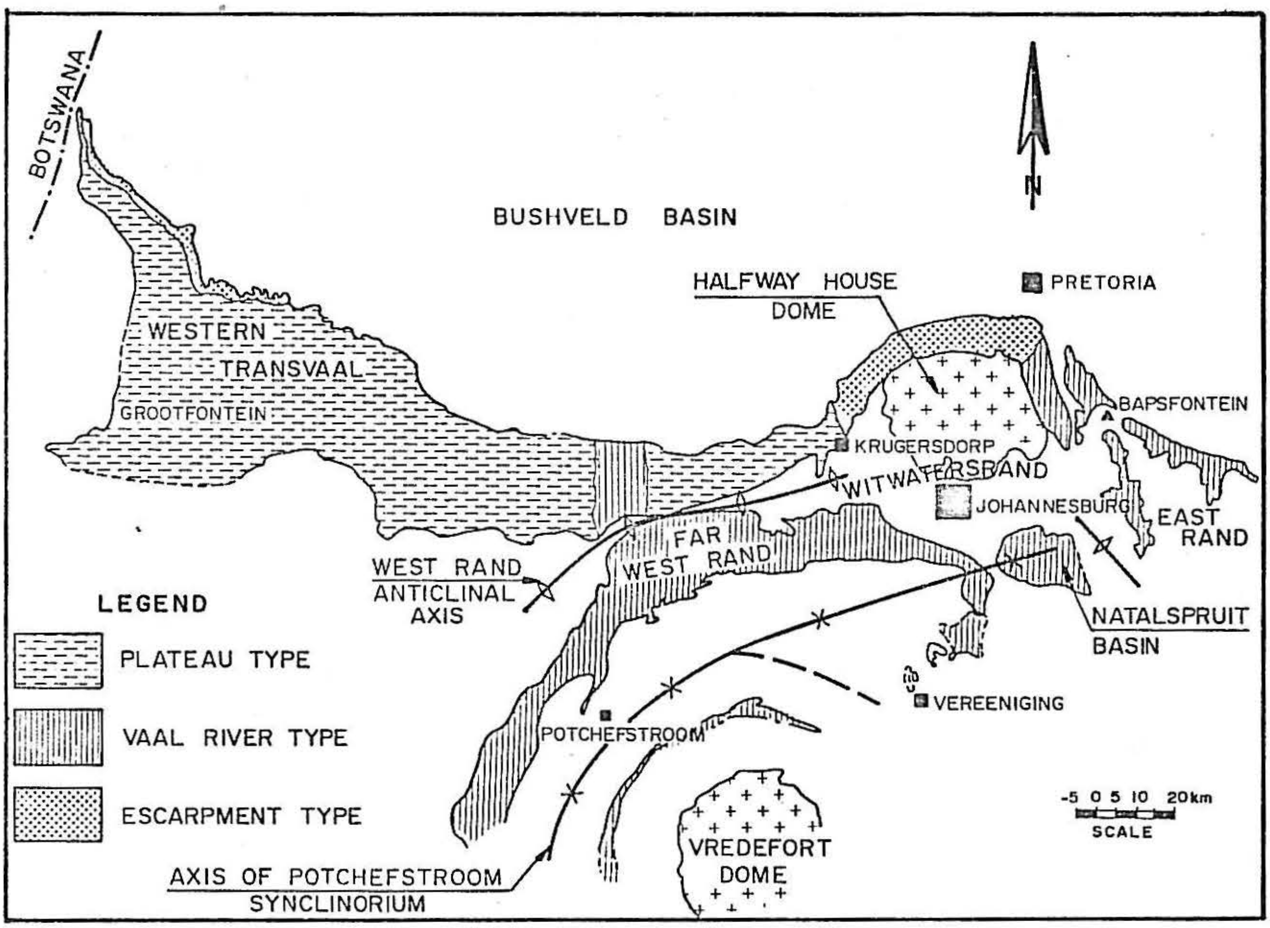


FIGURE 5. Distribution of karst morphological types (after Martini and Kavalieris 1976)

The existence of sinuous ridge-like diamondiferous gravel deposits in the western Transvaal which are the remains of palaeo-river courses, indicate that the present-day morphology has developed probably since the late Tertiary or Pleistocene (Du Toit 1951). Partridge and Maud (1987) on the other hand regard the surface as a lowered African erosion surface which dates back to early Cretaceous. The Plateau type morphology has evidently undergone little change over a long period.

(ii) The Vaal River type consists of wide, weakly-incised valleys developed on the flanks of the Potchefstroom synclinorium as well as southeast of Pretoria and carries perennial streams where the aquifers have not been dewatered by the gold mines. The karst topography is generally less obvious than the Plateau type. In contrast accessible caves are more numerous, including some of the larger systems found in South Africa.

(iii) The Escarpment type occurs between Pretoria and Krugersdorp. The name is derived from the type area which lies along the edge of the interior plateau in the eastern Transvaal. The topography is rugged and highly dissected and similar in most respects to that developed on the adjoining rock types. Caves are abundant and probably belong to the erosional cycle which produced the Plateau Type. Greater downcutting has occurred in this area. Valley floors are 150-200m lower than around Pretoria and Krugersdorp. Caves are now situated well above valley bottom level and occur perched on valley sides.

Marker and Moon (1969) found that cave levels in the Chuniespoort Group throughout the Transvaal occur on three preferred altitudes. These they relate to the African (Early Cretaceous), Post African (Early Miocene) and proto-Quaternary erosion surfaces. Detailed surveys on the Far West Rand by Martini et al (1977) suggest however that cave levels are governed by the elevation of springs which emerge where dykes cut the thalweg (figure 6).

Although caves are expected to develop more readily just below the water table, and this appears to be the case on the Far West Rand (Wolmarans 1984), Kleywegt and Enslin (1973) report that in this region leaching along tensional faults and fractures extends to depths of between 50m and 200m below the water table. Similarly, drilling in the Klip River Valley and elsewhere has shown that although the most intense dissolution occurs within a short distance below the water table, voids and cavities occur considerably deeper (figure 7).

Speleology

Martini and Kavalieris (1976), Martini et al (1977) and Moon (1972) provide descriptions of caves in this region. Fissure caves are probably the most common type. The largest known cave system has a combined passage length of 12,3 km . Most caves have a phreatic origin. Where the dolomite is intensely interbedded with chert layers, the carbonate component may be dissolved on both sides of the original joint without development of a cave passage - the chert and very porous "wad" remaining undisturbed and occupying the same volume as the unaltered dolomite. Irregular cavities develop by collapse and compaction of this residue.

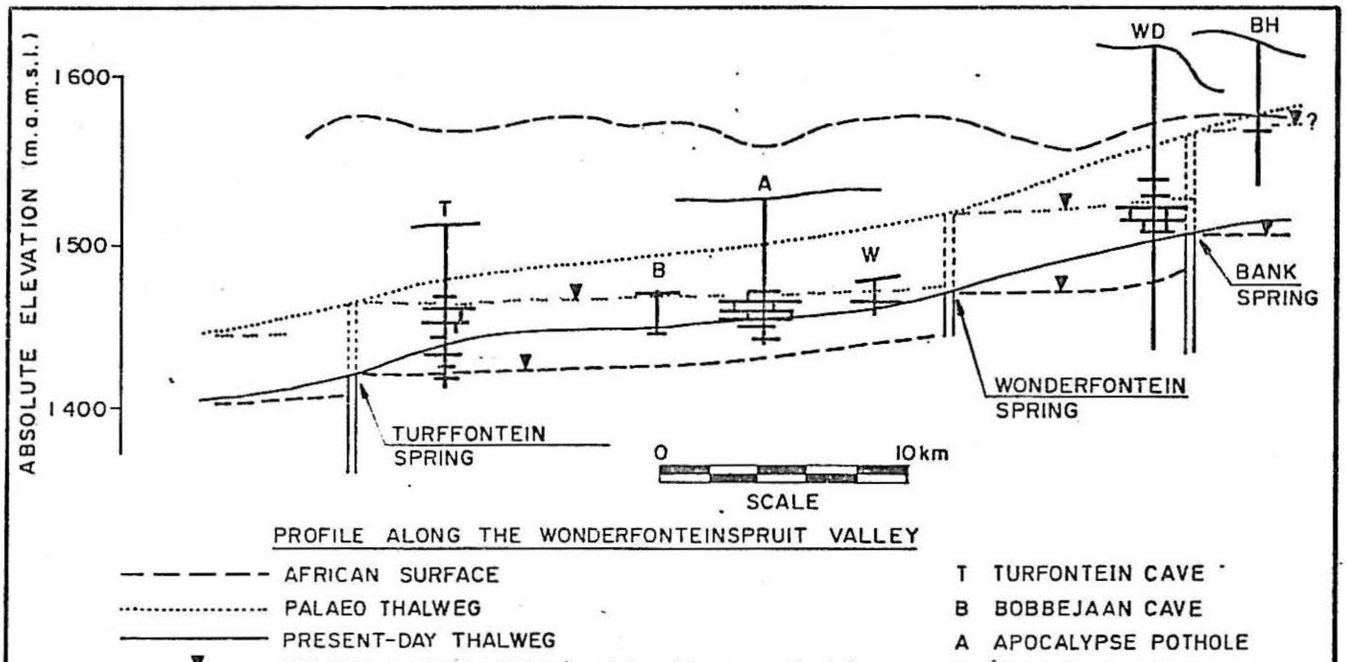


FIGURE 6. The effect of dykes on cave levels (after Martini et al 1977)

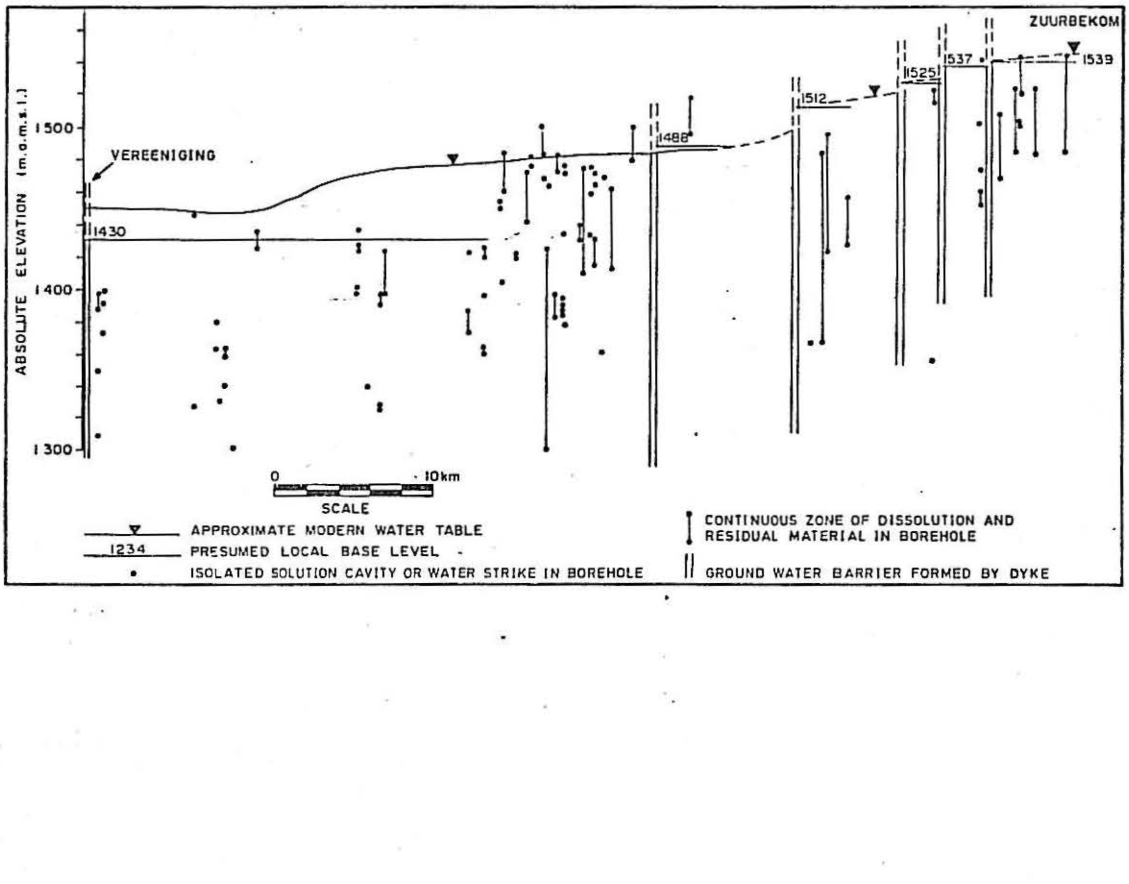


FIGURE 7. Profile along the Klip River Valley showing depths at which dissolution was recorded in exploration boreholes (from Foster 1988b, p.76)

A large number of caves owe their pattern to upward collapse of the roof of the original dissolution passage. The large water filled holes occurring in the Western Transvaal are due to collapse taking place below the watertable and are comparable with the cenotes of Yucatan. The upward progression of a collapsed chamber leads eventually to the development of a body of dislocated dolomite surrounded by a "ring cave". Most cave entrances are pit-like, being formed either by roof collapse of chambers or by the development of a sinkhole through a residual filling.

Present-day sinkhole formation and subsidence

Over the past 30 to 40 years, man's activities have led to a much accelerated rate of sinkhole formation and subsidence. These activities - principally urbanisation and mining - are responsible for the local disruption and concentration of surface runoff, for increased infiltration due to leakages from water and sewage mains and for the dramatic lowering of the piezometric surface in four ground-water compartments in the Far West Rand. These processes adversely affect the stability of the blanket of superficial deposits and the residual products of dissolution. Much has been written on this subject (see for instance Jennings et al 1965; Donaldson 1963; Brink and Partridge 1965; Jennings 1966; Kleywegt and Enslin 1973; Roux 1984) and the following should be considered only an outline of the most important aspects.

Kleywegt and Pike (1982) draw attention to the fact that in contrast to the properties of normal sedimentary sequences, the age and degree of compaction of the in-situ dolomitic residuum increases from the dolomitic bedrock upwards. This is the consequence of the continuing process of dissolution and formation of residual material. The residuum changes from the very low-bearing capacity, easily erodible wad and residual chert, directly above bedrock, through a mixture of chert and manganese oxides grading upwards into a compact chert breccia cemented by Mn and Fe oxides. This character of the residual deposits has an important bearing on sinkhole formation and subsidence.

It is generally accepted that sinkholes occur through the progressive collapse of arches or domes which span air-filled voids in the residuum. The conditions for the formation of sinkholes have been detailed by Jennings et al (1965) as follows:

(i) Abutments for the roof of a void provided by dolomite pinnacles or the sides of grikes.

(ii) Development of arching conditions in the residuum.

(iii) Development of a void below the arch.

(iv) A reservoir to accept material which is removed to enlarge the void and a means of transportation such as water.

(v) A disturbing agency to cause roof collapse. Water in the arched material in the vadose zone leads to loss of strength, erosion and removal of binding material. In the phreatic zone dewatering leads to a loss of buoyant support.

Subsidence is generally ascribed to a lowering of the water table through unconsolidated residuum which results in compaction and the formation of depressions which often have small scarps at the margins. Kleywegt and Pike (1982) contend that apart from compaction, collapse also plays a role. Figure 8 illustrates the different conditions for the formation of sinkholes and compaction.

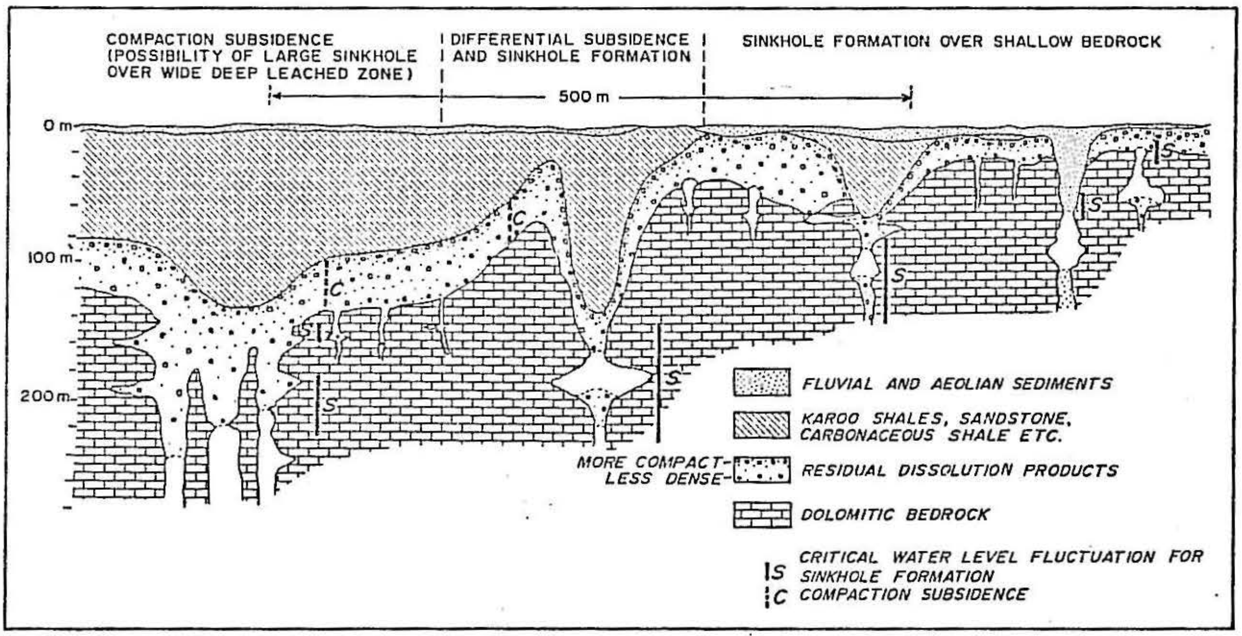


FIGURE 8. Semi-diagrammatic depiction of karst conditions on the Far West Rand illustrating presumed critical watertable drawdown/fluctuation for compaction and sinkhole formation (after Kleywegt and Pike 1982 fig. 4.2)

The sinkhole and subsidence hazard caused by dewatering places a serious constraint on the utilization of the large volume of ground water held in dolomitic strata for an emergency supply to the metropolitan PWV area (Vegter 1987).

Geological control of karst development

General

The present level of knowledge about the karst development in the Chuniespoort dolomitic strata is the result both of field observations and the examination of caves, as well as extensive detailed gravity surveys and drilling undertaken for geotechnical reasons and the assessment of ground water resources. The gravity method has been found to be the geophysical method best suited for determining the configuration of dolomitic bedrock as a result of the density contrasts between fresh dolomite and the various types of cover material (see Table 1). A typical profile combining gravity and geology is presented in figure 9.

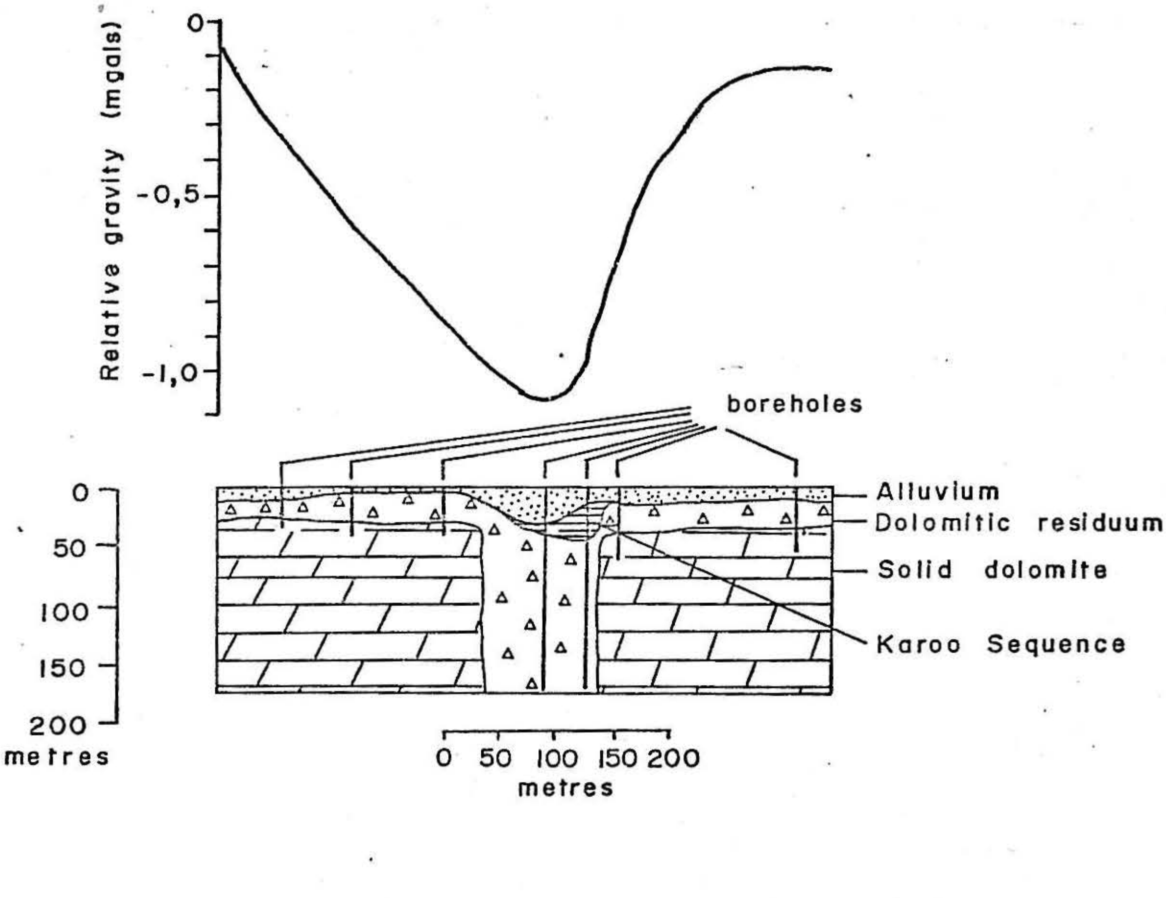


FIGURE 9. Geological profile across gravity low in the Far West Rand (after Kleywegt and Enslin 1973)

TABLE 1: Average density values for bedrock and overburden occurring in areas underlain by the Chuniespoort Group (after Enslin et al, 1976)

Lithology	Average density value (kg/m^3)
Fresh dolomite	2850
Incompletely leached dolomitic bedrock	2600
Overburden material (surface deposits, wad and incompletely leached dolomitic bedrock)	2350
Karoo Sequence sediments	2000-2400
Surface deposits	1600
In-situ completely leached zone with inverse density variation with depth: compact cemented chert breccia with density of 2600 kg/m^3 over horizon of porous wad of 1000 to - 1200 kg/m^3	2100

Lithostratigraphy

At surface the chert-free dolomite units weather forming karren or dolomite pavements (lapiés) where the normally roundly weathered blocks are separated by soil-filled grikes. Despite a high density of incipient joints major dissolution occurs only on well spaced discontinuities. The cherty units have rugged outcrops; the resistant chert supporting large voids resulting from the dissolution of the carbonate rock. Where observed at outcrop dissolution occurs on many more joints and bedding planes in the alternating chert and dolomite sequences than in the chert-poor units.

These different weathering characteristics continue below surface as illustrated in figure 10. Ground water exploration drilling south of Johannesburg showed that in the chert-rich formations water-bearing zones attained thicknesses up to 60m. The aquifer material in such zones has been described as very fractured and weathered chert, or similar, and often with

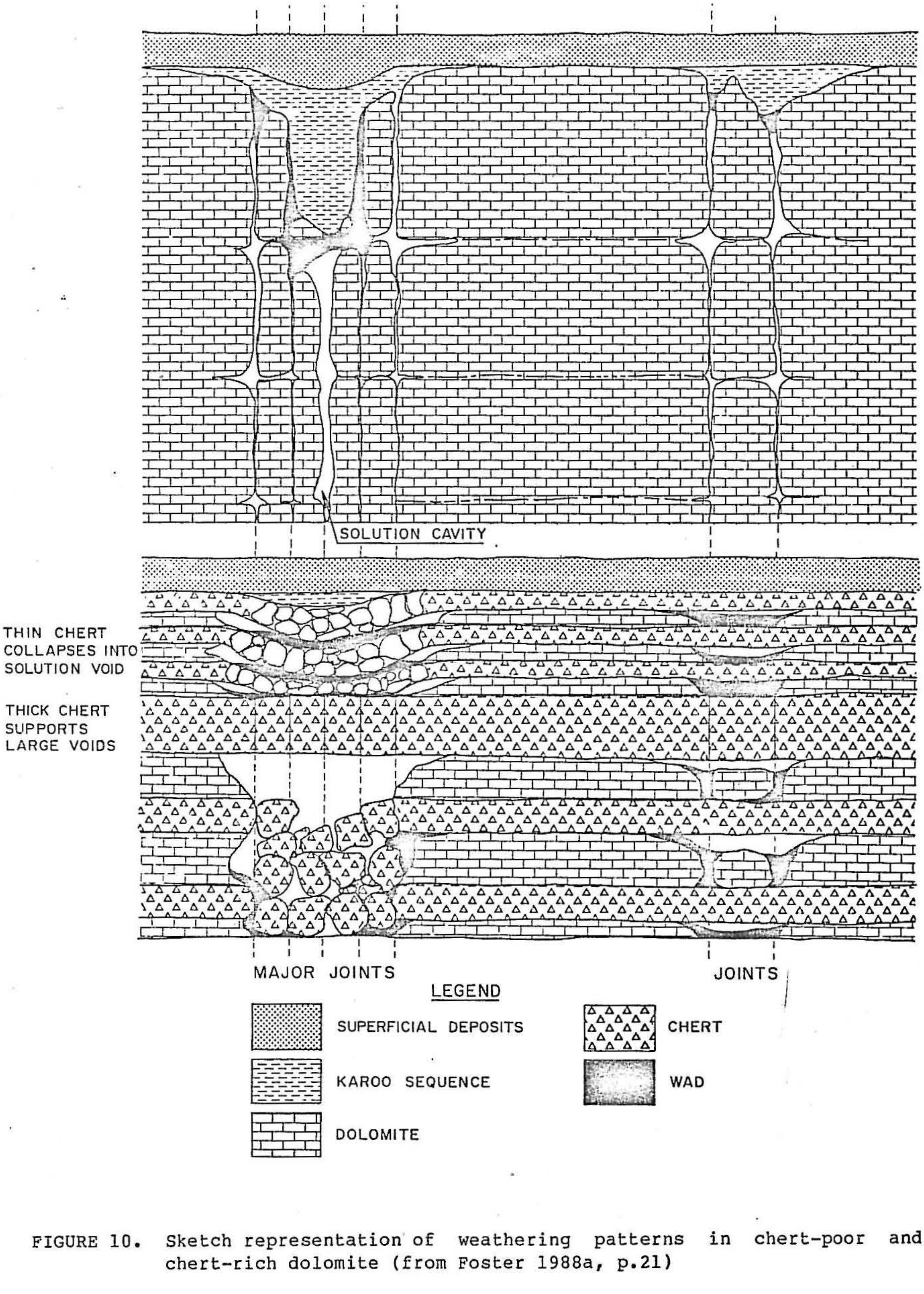


FIGURE 10. Sketch representation of weathering patterns in chert-poor and chert-rich dolomite (from Foster 1988a, p.21)

little evidence of any dolomite (borehole log B, figure 11). Near the Pretoria Group outcrop some chert may be chert breccia of the Rooihoogte Formation and not weathered Chuniespoort Group.

Within the chert-poor Oaktree and Lyttelton Formations all water strikes occur as discrete dissolution features in fresh dolomite. The maximum proven thickness of these features below water level is three metres. Water strikes are commonly associated with thin bands of shale or chert (borehole log A, figure 11).

Gravity anomaly maps in the Klip River Valley reveal zones of preferential weathering of the chert-rich Monte Christo and Eccles Formations, and that extensive zones of porous and permeable material only form where the weathering of closely spaced geological structures coalesce in either of these units (figure 12). Because of the small volume of coarse residual weathering products resulting from the dissolution of the chert-poor units of the Oaktree and Lyttelton Formations, extensive gravity lows tend to be infilled with wad and semi-permeable Karoo Sequence deposits (figure 10).

Palaeokarst

Throughout the south central and western Transvaal water-bearing zones commonly occur at the pre-Karoo palaeokarst surface, especially where gravity anomaly maps indicate deeper weathering of the dolomitic formations. The occurrence of good aquifer conditions in these weathered zones is dependent upon the presence of coarse porous material (generally chert) preventing the ingress of the clayey residue (weathered Karoo or wad) into boreholes. Differentiating between in - situ weathered chert and transported chert debris from drill cuttings is problematic and leads to uncertain interpretation of the detailed hydrogeology.

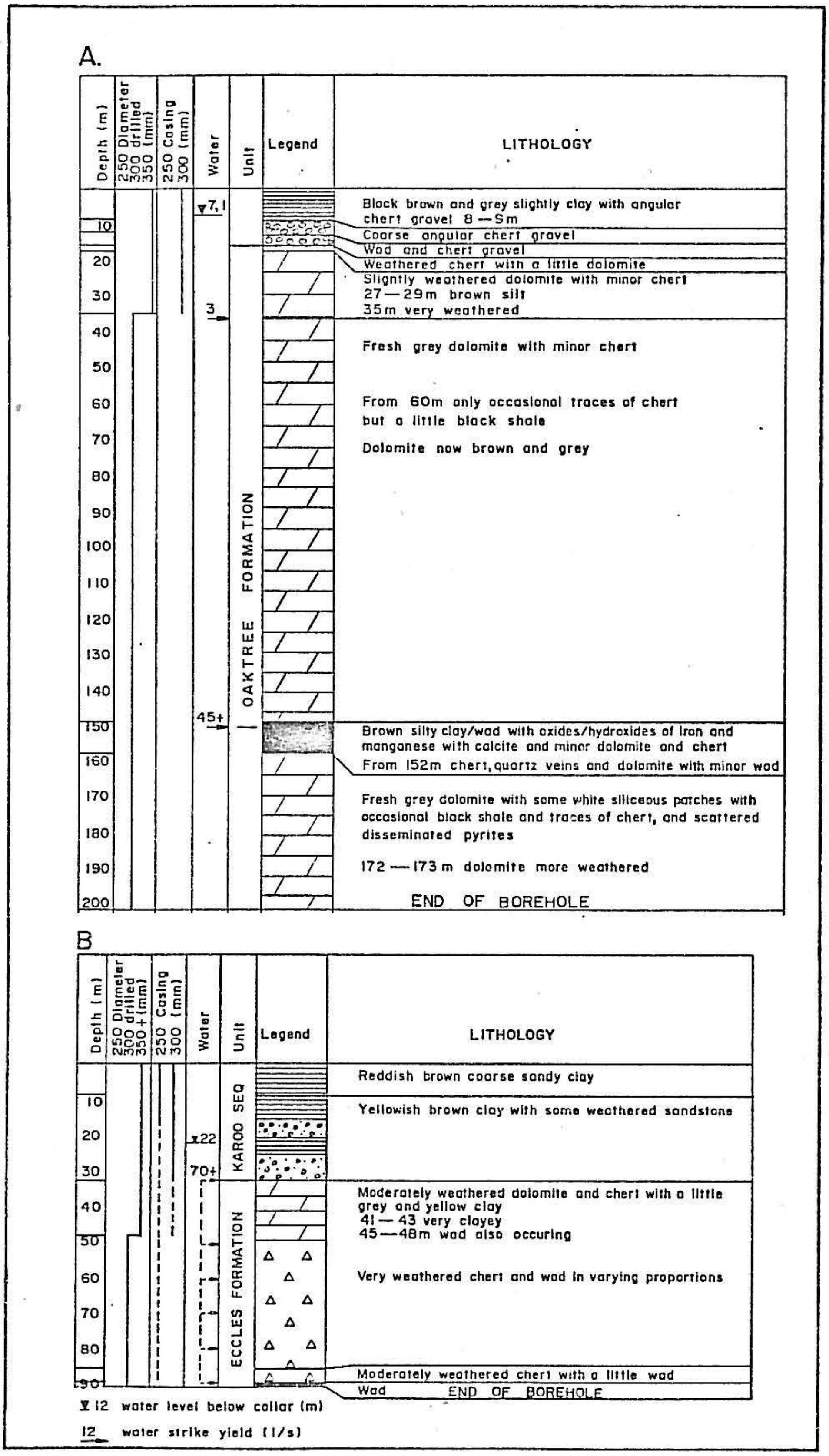


FIGURE 11. Borehole logs showing typical aquifer conditions of A. chert-poor dolomite and B. chert-rich dolomite

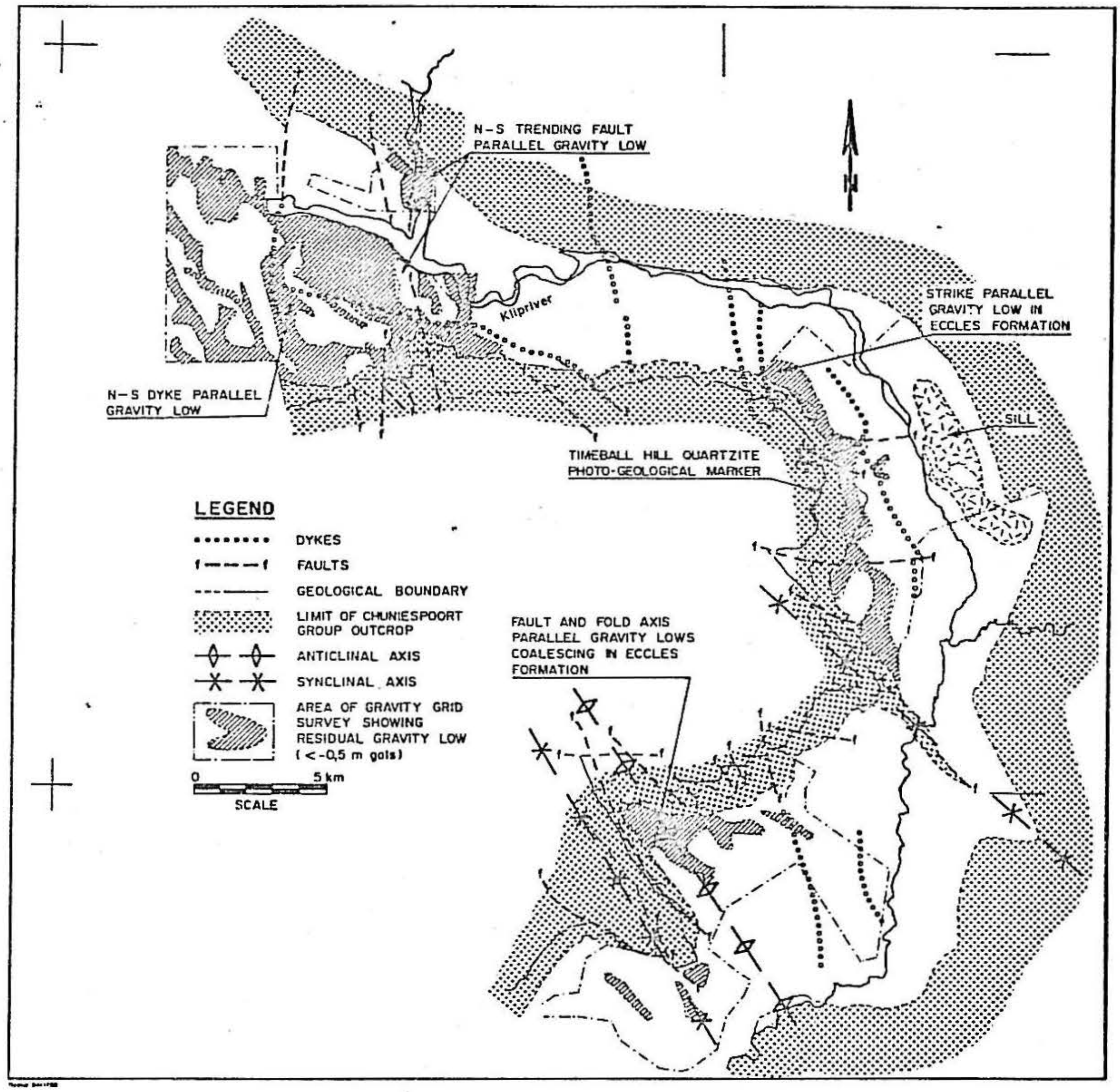


FIGURE 12. Structural geology and gravity lows in the Klip River Valley (after Foster 1988a)

The unconformities within the Chuniespoort Group were also periods where the carbonate rock may have been exposed to karst erosion. Several ground water exploration boreholes obtained good water supplies after penetrating these horizons in excess of 200m below ground surface, beneath extensive thicknesses of unweathered dolomitic strata. This effect could also be attributed to bedding-parallel structural features.

Jointing and faulting

The control exerted by jointing and faulting upon karstification processes is evident from cave surveys (figure 13) as well as residual gravity maps (figure 12). Kavalieris and Martini (1976) and Moon (1972) have shown the most important direction of cave passages west of the Halfway House dome to be more or less east-west with another more or less perpendicular to it. Kavalieris and Martini (op cit) relate the orthogonal pattern to post-Karoo crustal arching along a NNE-SSW axis. The major east-west joint set is comparable to the dominant strike trend of the post-Karoo dykes. Others have associated the joint controlled cave development to both older and more localised structural features (Partridge and Brink 1965 and Moon 1972).

The dissolution pattern which emerges from residual gravity maps is more complicated than is evident from the cave surveys. Easterly and northerly trending linear zones of deep leaching run parallel with both the post-Karoo as well as the Pilanesberg and East Rand dyke systems in figure 2. These linear zones of dissolution result from enchanced weathering along joints and fissures due to the crustal tension associated with the emplacement of dykes. The continuity of these linear zones of dissolution is often unaffected by lithostratigraphy. Exploratory drilling has confirmed dissolution channels in excess of 50m wide as shown in figure 9. The hydrogeological characteristics of these zones are dependent upon the nature of the residual and transported material filling them (refer back to lithostratigraphic control of karst).

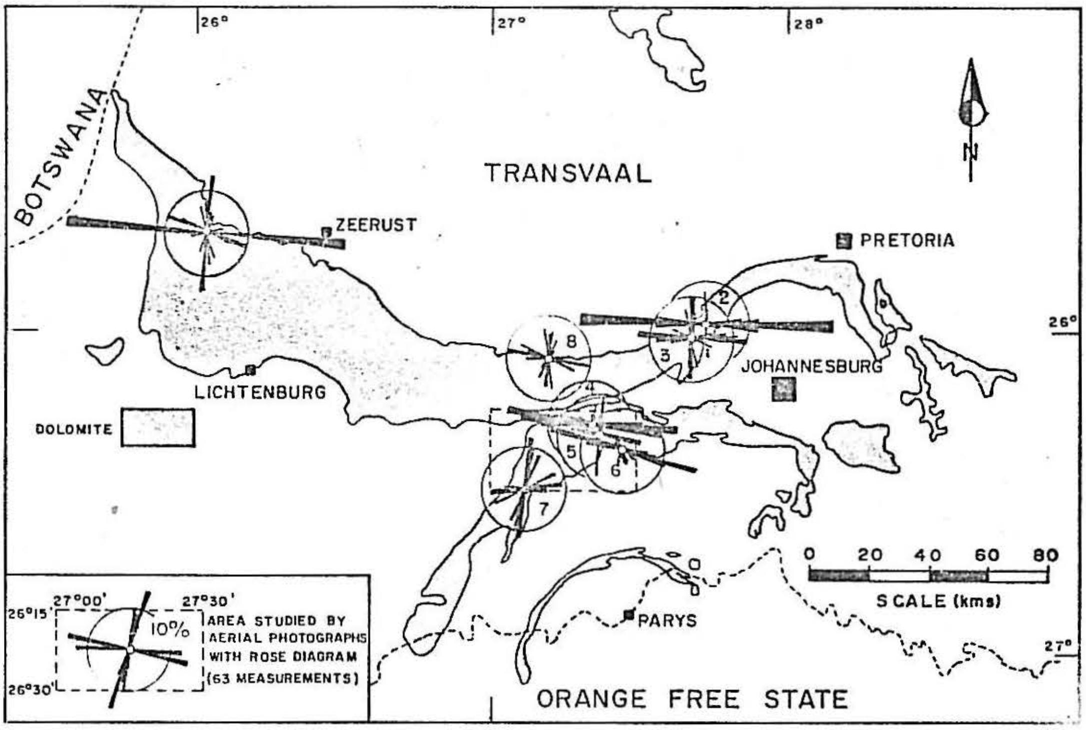


FIGURE 13a Strike of cave passages in south-central and western Transvaal (from Kavalieris and Martini 1976 p. 309)

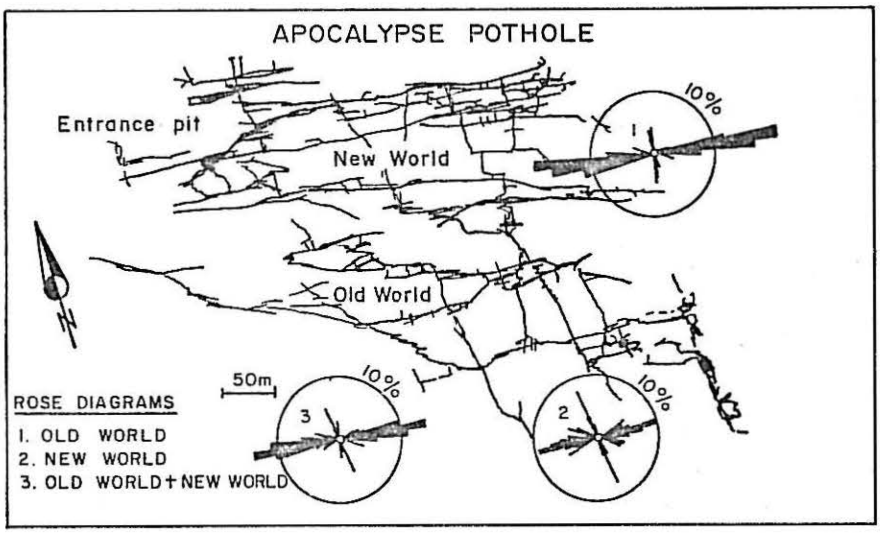


FIGURE 13b Strike of fissures in largest known cave in south-central and western Transvaal (from Kavalieris and Martini 1976 p. 309)

Some north-westerly and north-easterly features have been connected with faults encountered in gold mining. The complex pattern of crossing linear zones is evident on the gravity anomaly map of the Gemsbokfontein Compartment (figure 14).

De Kock (1964) mentions the existence on the Far West Rand of a number of post-Transvaal tension faults of relatively small vertical displacement which trend roughly parallel to the N-S Pilanesberg dyke system and which feed dolomitic ground water into the mine workings. The inrush of dolomitic ground water into West Driefontein Gold Mine at a rate of more than 360 000 m^3/day in 1968 (Taute 1971) is a powerful example of transmissive zones occurring to great depths. A low angle normal fault was found to be the cause (Wolmarans 1984).

Dykes

Discontinuities or steps in the piezometric surface which are usually observed across dykes indicate that they act as barriers to ground-water flow, and divide the dolomitic strata into separate ground-water units or compartments (figures 2 and 6). Residual gravity data indicate that in places dyke contact zones are favourable loci for dissolution of the dolomitic strata (figure 12).

Sills

Sills also act as barriers to ground water movement. On the East Rand water is commonly encountered in boreholes on or near the upper and lower contacts of three sills. On the other hand in the Natalspruit basin, between Vereeniging and the East Rand, the contacts of a 80 metre thick post-Karoo dolerite sill have not yielded any water.

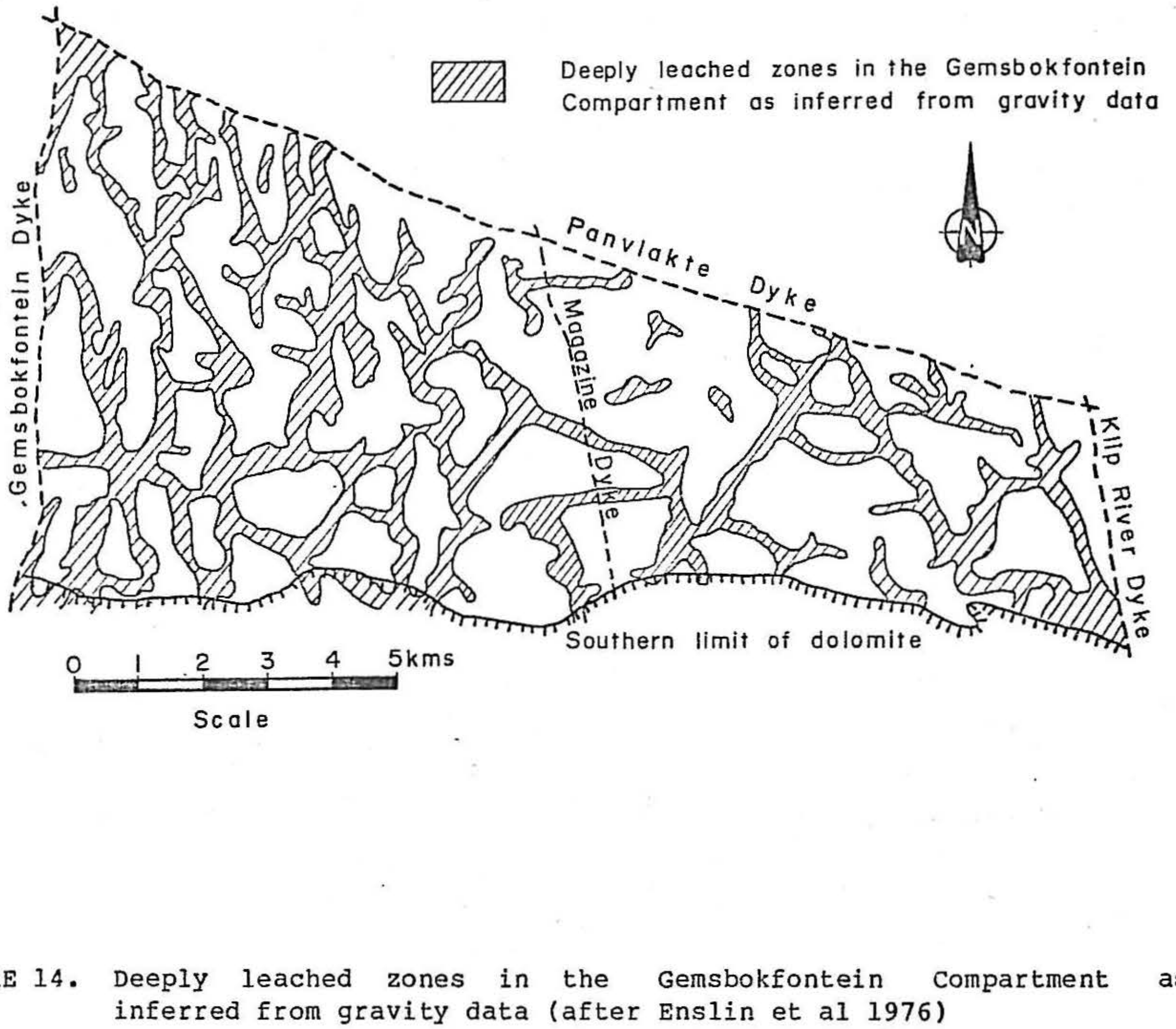


FIGURE 14. Deeply leached zones in the Gemsbokfontein Compartment as inferred from gravity data (after Enslin et al 1976)

Folding

In general folding appears to play only a minor role in karst development. At one location north of Vereeniging however karst development is associated with a NW SE striking anticline and a coincident zone of faulting (figure 12).

Aquifer characteristics

The mantle of transported material and residual dissolution products, together with the underlying zone of cavernous to fractured bedrock constitute aquifers capable of holding and transmitting large volumes of water. Fractures, some of which extend through the whole dolomitic succession connect the upper water-bearing zone to deeper-lying aquifers in the dolomitic bedrock. Where present, Karoo strata act as semi-confining beds and give rise in places to temporarily perched ground-water bodies. Figure 15 is a semi-diagrammatic representation of hydrogeologic conditions in the Wonderfontein valley.

As has already been mentioned, dykes have a profound influence on the hydrologic regime, by acting as barriers or partial barriers to ground-water movement and thus dividing the dolomitic strata into separate hydraulic units or compartments. Mine dewatering on the Far West Rand has produced head differences of several hundred metres between adjacent compartments as a result of the effect of these dykes. Surface and/or subsurface flow may occur between compartments. On the surface, ground water crosses the dykes after issuing as springs on the upstream side. Subsurface flow may occur at gaps in the dykes; where faults displace dykes and/or where weathered and fractured dyke rock extends to below the ground water level.

Numerous methods have been used to determine aquifer storativity and transmissivity which vary widely depending on the degree of karstification and the nature and thickness of the saturated mantle. Analyses of pumping test

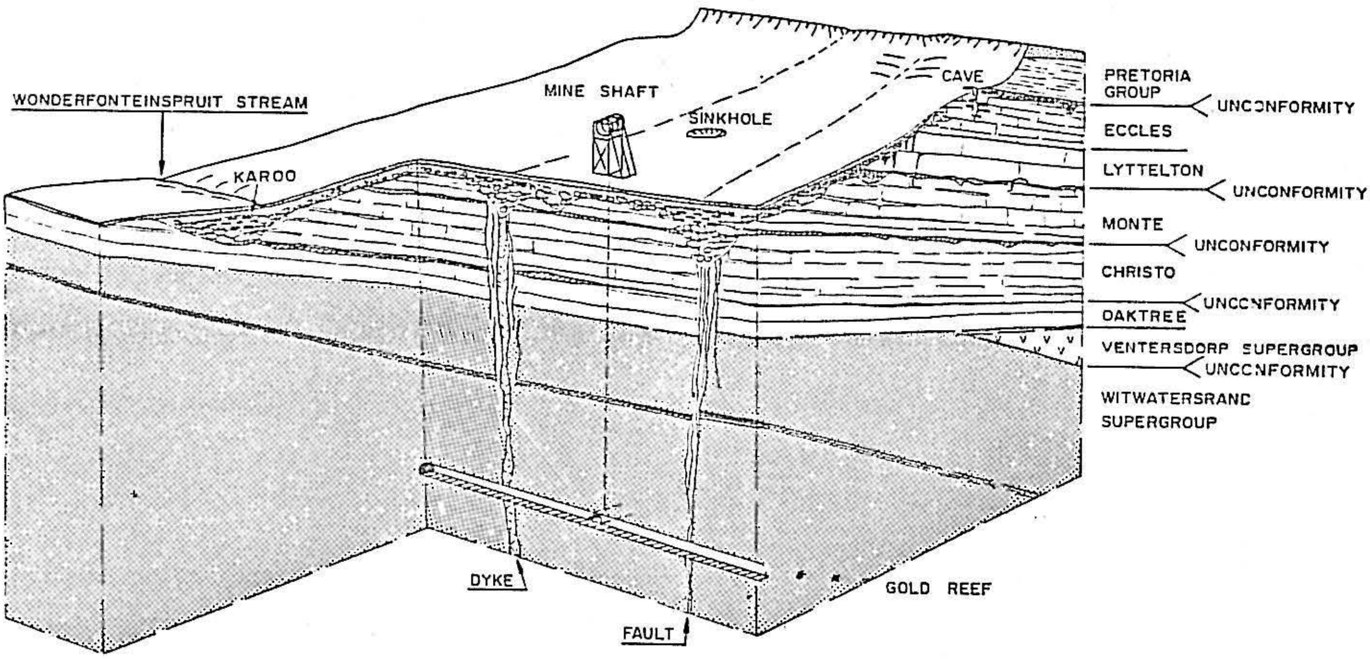


FIGURE 15. Schematic representation of aquifer conditions along the valley of the Wonderfonteinspruit stream

data and of the catastrophic flooding of the West Driefontein Gold Mine in 1968 have produced storativity values varying between 0,0005 and 0,069 (see inter alia Bredenkamp and Vogel 1970; Fleisher 1981; Schwartz and Midgley 1975). Ground water and chemical mass balances for individual ground-water compartments have yielded effective porosity values of between 1,0 and 3,4 percent. Detailed analyses of the dewatering of several ground water compartments by gold mines, as well as shaft and borehole logs, have shown that in good aquifer zones effective porosity may vary from as high as 14 percent at the water table to less than 2 percent at 150 metres below the surface (Enslin and Kriel 1959; Foster 1987).

Transmissivities range from less than $10m^2/d$ to nearly $30\ 000m^2/d$ (see inter alia Enslin and Kriel 1959; Schwartz and Midgley 1975; Fleisher 1981; Bredenkamp and Janse van Rensburg 1983). Poor transmissivities are evident from piezometric gradients in the order of 1:50 whilst in the highly transmissive parts gradients as low as 1:5000 have been recorded. Natural flow velocities are therefore very low except near the emergence of springs. Tracer experiments using NaCl, fluorescein and radioactive isotopes showed that where mine dewatering had produced a cone of depression in excess of 100 metres deep, water recharged through boreholes at surface could enter mine workings within 24 hours (West Driefontein Mine, personal communication).

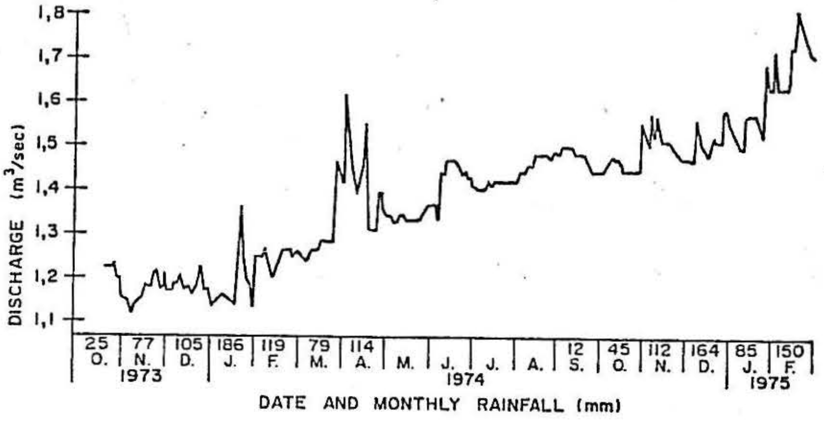
Hydrology

Most springs issue on or near the contacts with dykes, with the underlying quartzitic Black Reef Formation or with the overlying clastic rocks of the Pretoria Group. The positions of some springs in the Western Transvaal are governed by chert beds and others by extensive quartz veins. Flows range from less than 1 l/s to about $3m^3/s$ at Schoonspruit Spring, the strongest. The more important springs have fairly constant flows which do not deviate by more than 40 to 65 percent from the mean. No proper study has been made of daily fluctuations and of the early responses of springs to rainfall events. It would appear that the responses, in general, are relatively small compared to total flow.

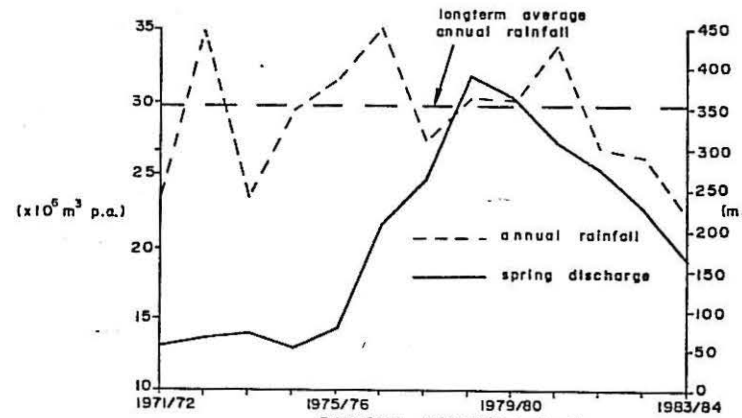
Fleisher (1981) states that in contrast to springs rising from karstic terrains in many parts of the world, most springs here show no annnual recession. The lack of an annual recession under a regime of summer season rainfall is ascribed by Fleisher to a two-phase system of recharge whereby each rainfall episode would affect the aquifer twice : firstly, by rapid downward conduit-type flow via fissures and fractures beneath areas with a thin or absent cover of permeable superficial deposits, and later, by slower diffuse percolation through a thick cover of soil and lesser permeable materials. The simultaneous response of spring flow to changes in piezometric level supports this contention. With delayed recharge continuing through the dry winter season, recession of flow does not occur (figure 16a).

Most of the spring hydrographs show that exceptionally high rainfall seasons are followed for a period of three to four years by above-average spring discharge. This is well illustrated by the hydrographs of Maloney's Eye (figure 16b). Similar fluctuations of the piezometric level have been observed in the Wondergat sinkhole in the western Transvaal and elsewhere (figure 16c). This phenomenon can be ascribed to the delayed recharge as well as limited outflow at the springs.

(a)



(b)



(c)

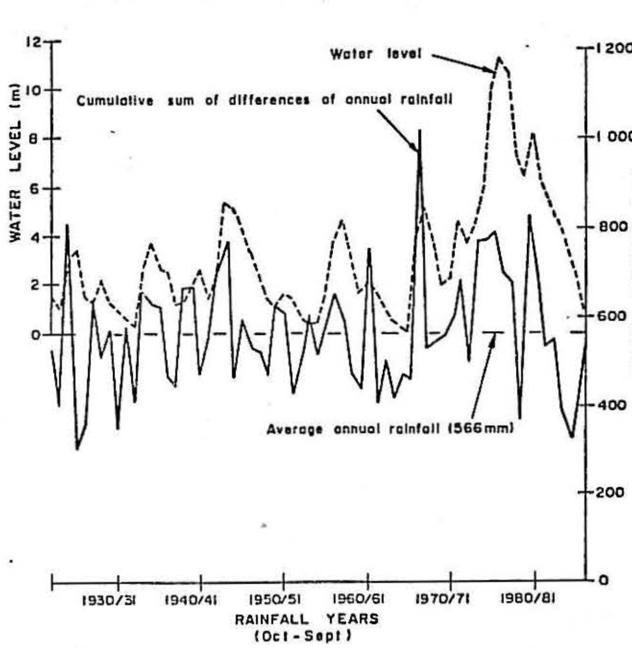


FIGURE 16. (a) Schoonspruit spring discharge hydrograph showing immediate summer rainfall recharge and continued recharge in winter months (after Fleisher 1981, pp.219)

(b) Maloney's Eye discharge hydrograph showing long term response to exceptionally high rainfall years.

(c) Wondergat water level fluctuations in response to high rainfall years.

Ground water replenishment by rainfall in compartments lacking surface streams has been estimated by means of ground water balances and other methods. Mean annual recharge has been found to range from some 60mm in the west to about 110mm in the east. The ratios of storage to mean annual recharge from Table 2 reveal that total aquifer storage is generally much greater than the annual recharge, and also indicate that maximum aquifer throughflow time should be in the order of 100 years.

TABLE 2 Ground water storage and recharge for selected dolomitic ground water compartments.

Compartment	Surface Area (km^2) (A)	Original volume storage $10^6(m^3)$ (B)	Effective water column height (m (B/A)	Mean annual recharge (mm)	Storage/mean annual recharge
Grootfontein (Western Tvl.)	128	220	1,718	70	25
Ventersspost (Far West Rand)	54	460	8,5	85	100
Oberholzer (Far West Rand)	150	1050	7	85	82

Hydrochemistry

The results of some 500 chemical analyses of ground water in the Ventersdorp area have been reproduced in the form of a Durov diagram (figure 17). The picture may be considered as typical of uncontaminated dolomitic ground water in south-central and western Transvaal.

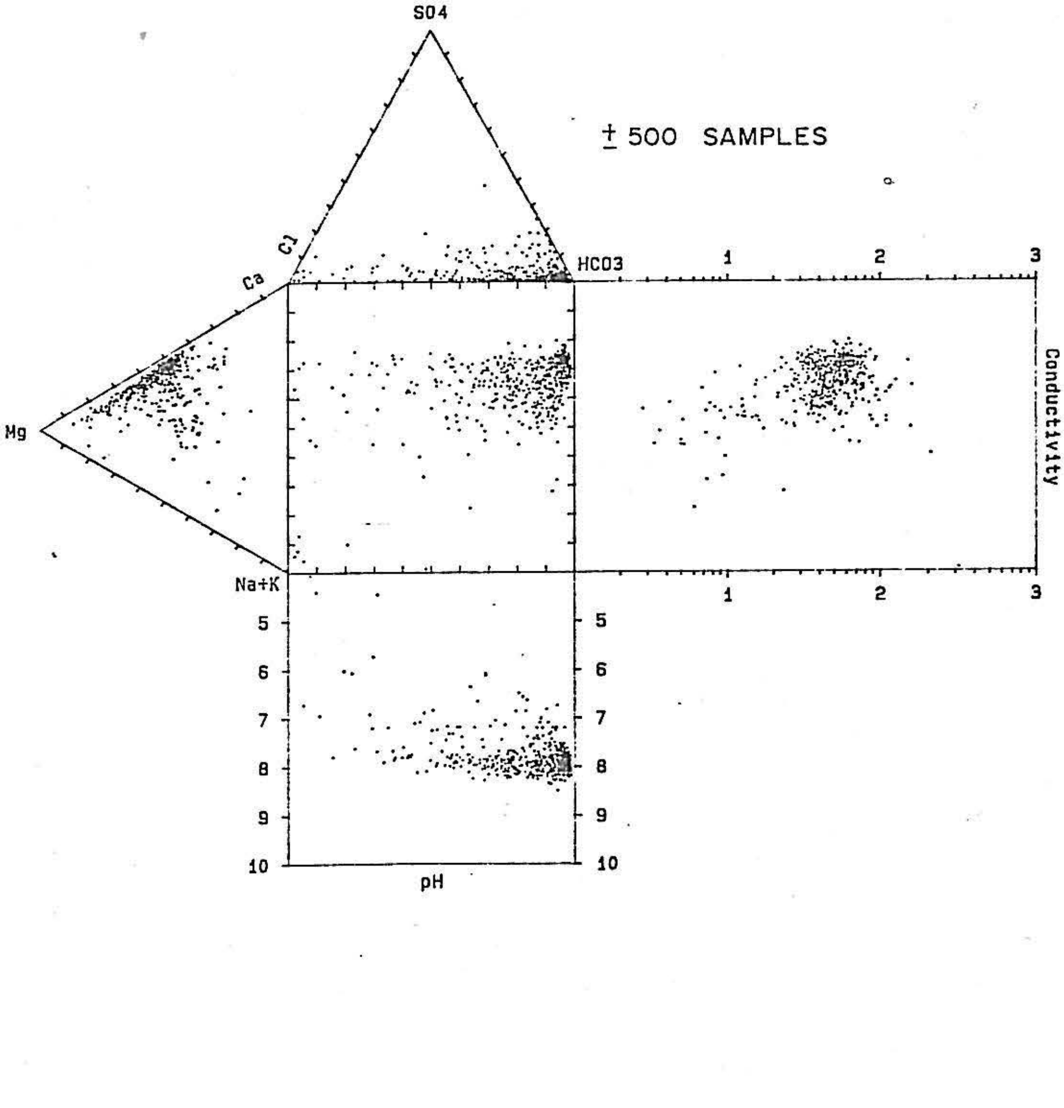


FIGURE 17. Expanded Durov diagram of ground water samples from the Ventersdorp area

The distribution of ionic Ca:Mg ratios of 58 ground water samples from the Bapsfontein area are shown in histogram form in figure 3. Compared to that of the dolomitic strata there is flattening and widening of the distributions. This is contrary to the findings of Bond (1964) and Martini (1972) who state that enrichment of Mg relative to Ca has taken place.

Although natural isotope studies have been undertaken (e.g. Bredenkamp and Vogel 1970) interpretation of the results remains problematic. A proper interpretation is not possible without detailed knowledge of the recharge mechanisms and flow pattern in an extremely heterogeneous aquifer. Originally it was anticipated that the age of water emanating from a spring would represent the average age of water in storage and accordingly provide an easy means of assessing storage capacity of a compartment in terms of the mean annual discharge of the spring rising from it. The radio carbon content of a few dolomitic springs in the western Transvaal was found to vary largely - corrected ^{14}C ages ranging from modern to as much as 2000 years. The latter high ages appear to be incompatible with the ratios for annual recharge to storage quoted in the previous section 'Hydrology'.

CONCLUSIONS

Varying depositional and diagenetic environments in the Pre-Cambrian resulted in dolomitic formations with fundamentally different weathering characteristics. Unimpeded downward percolation of aggressive groundwaters.in vertical joints, faults and fissures has caused the chert-poor Oaktree and Lyttelton Formations to develop karstic solutional porosity along well spaced solution channels. Ubiquitous chert beds and laminations in the Eccles and Monte Christo Formations encourage horizonal development of carbonate dissolution. The transmissive zones in the chert-rich units thereby comprise a much thicker and more extensive chert supported porous permeable zone.

The effects of a palaeokarstic episode may be evident from gravity anomaly maps and drilling, as in the case of the pre-Karoo surface; or indeterminate due to subsequent erosion, as in the case of the pre-Waterberg period; or they may be obscure due to their occurrence at depth within the dolomitic bedrock. All the erosional episodes however, both during Chuniespoort sedimentation as well as in subsequent periods have affected the whole of the Transvaal Basin.

Lithostratigraphy and palaeokarst history are therefore the major controls on the development of the karst aquifer in the Chuniespoort Group. They are the only hydrogeological factors which effect the aquifer development throughout the whole south-central and western Transvaal. Knowledge of the lithostratigraphy and palaeokarstic history is therefore crucial for an understanding of the fundamentals of the hydrogeology of this karst region.

Although extensive erosion surfaces form major elements of todays southern African landscape, karst erosion levels are locally determined by the level of erosion of the dykes which form ground water barriers. The retardation of the ground water flow by the dykes has presumably reduced the rate of carbonate dissolution but may have allowed more complete dissolution at certain horizons by maintaining the height of ground water levels for greater periods than would otherwise have been the case without dykes.

The great age of the Chuniespoort Group has meant the exposure of the strata to numerous periods of tectonism, igneous intrusion and sub-aerial erosion, starting in the early Proterozoic within Chuniespoort Group times through to present day active karst conditions. It is therefore not surprising that there are many other factors exerting a controlling influence on the development of the karst aquifer. Throughout the south-central and western Transvaal folds, faults, joints, lineaments, dykes and sills have all been found to be associated with zones of greater dissolution and hence greater transmissivities and storativities. None of these, however, dominate karst development over the whole of this region. In any given area there is normally one dominant structural or intrusive feature where karst is developed to its maximum.

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