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 (Fig. 1) and attain maximum thicknesses of 1,880 and 1,600 m 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 2,300 Ma. In this paper, attention will be focused only on the south-central and western Transvaal.

This region contains the highly populated and industrialized 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 human 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 programs in order to delineate potentially unstable ground (Kleywegt and Pike, 1982). Rapid urbanization 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 reservoir levels.

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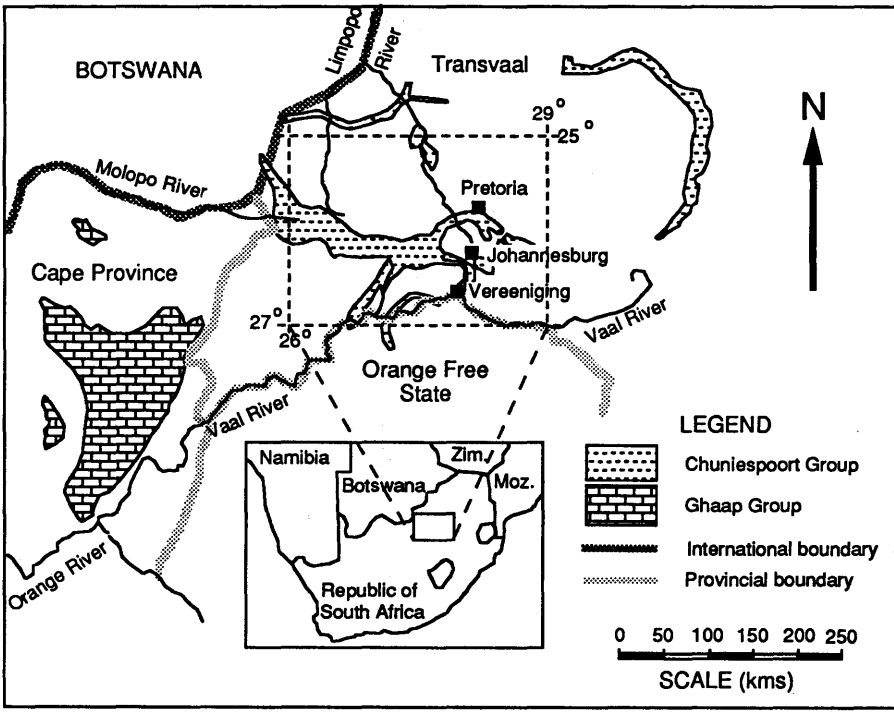


Figure 1. Distribution of Proterozoic dolomitic strata in the Northern Cape and Transvaal.

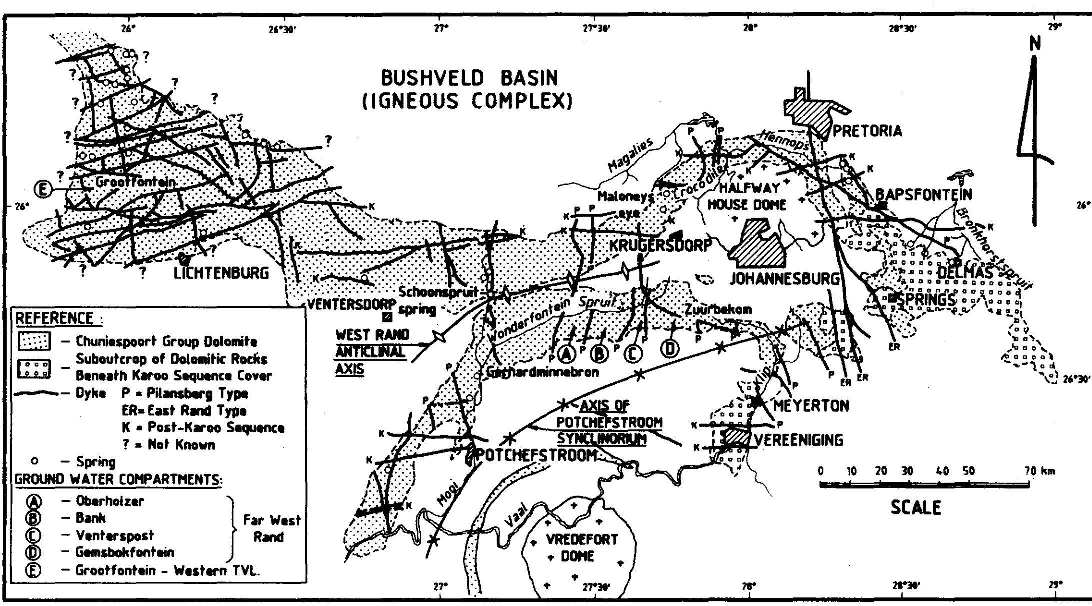


Figure 2. Dikes and ground-water compartments in south-central and western Transvaal.

The area under description (Figs. 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 1,750 m at Johannesburg and 1,400 m at Potchefstroom to 1,460 m at Lichtenburg. The climate is warm temperate with summer convectional rainfall varying across the area between a mean of 640 mm in the west to 730 mm in the east. Annual potential evaporation varies between 1,400 mm and 1,800 mm.

GEOLOGY

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 12,000 m thick succession of clastic and chemical sediments and volcanic rocks of the Transvaal Sequence. The Chuniespoort Group attains a thickness of 1,200 m on the Far West Rand, and near Bapsfontein a thickness of 1,000 m has been recorded.

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 (Fig. 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: 1) chert-free micritic or recrystallized dolomite and 2) chert-rich dolomite composed of alternating beds, bands, and laminae of chert and dolomite.

Geochemistry

Samples of drill cuttings taken at one-meter intervals from five boreholes penetrating different stratigraphic horizons in the Bapsfontein area have been analyzed using X-ray fluorescence. The CaO content of the rock was found to vary from about 10 to 35% and the MgO content from about 8 to 21%. SiO_2 content ranged from less than 1 to over 60% in chert-rich zones. In 84.5% of the samples, the Ca:Mg ratio exceeds the theoretical value for pure dolomite (molar Ca:Mg ratio of 1:1 equivalent to a 1:0.72 ratio by weight of CaO:MgO).

Samples taken south of Pretoria show that the FeO content varies from less than 0.1 to 6.1% and MnO ranges from about 0.2 to 3.7%. 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 tens of parts per million are also present. It is believed that these chemical data are representative of the whole area under discussion.

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).

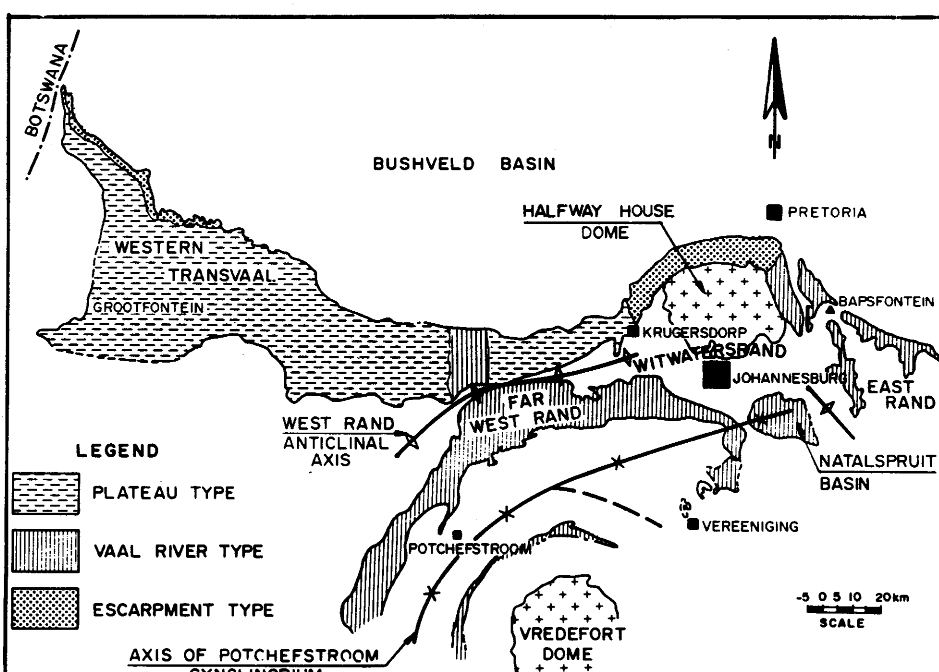


Figure 4. Distribution of karst morphological types (after Martini and Kavalieris, 1976).

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. The chert-rich Monte Christo and Eccles Formations are characterized by oolites, lamination, and ripple marks as well as columnar and domal stromatolites with a maximum relief of 1 m. These features are diagnostic of an intertidal to supratidal environment comparable to the modern examples of Shark Bay, Western Australia, and the tidal and freshwater marshes of the Everglades, Florida. Large elongate domal stromatolites of the chert-poor Oaktree and Lyttelton Formations are up to 16 m long and 3 m in relief. The only known stromatolite forms growing today comparable in size occur in the subtidal environment of the Eastern Bahama Bank.

There has been no extensive petrological or isotopic studies of the Chuniespoort Group dolomites to aid our understanding of the diagenetic history of these carbonates. Both the dolomite and the chert are probably replacement minerals but they are present in widely differing proportions in the different lithostratigraphic units of the Chuniespoort Group. It is therefore likely that the results of diagenesis are linked to either the depositional environment or compositional differences in the original carbonate sediments. Seawater-freshwater mixing zones have been considered to provide suitable geochemical conditions for the processes of both dolomitization and silicification (Hanshaw et al., 1971; Badiozamani, 1973; Knauth, 1979). Using a seawater-freshwater mixing zone model the presence or absence of chert may be explained by mixing zone migration history. The subtidal chert-poor dolomites were deposited in a gradually subsiding basin where the mixing zone would have undergone a one way migration. The stromatolite morphology of the chert-rich units record a series of minor transgressions and regressions which would have been accompanied by similar back and forth movement of the mixing zone. This interpretation is difficult to apply however to the units of the Chuniespoort Group where fine interlamination of dolomite and chert would require rapid oscillation of the mixing zone position. This very small scale variation has been interpreted as a reflection of depositional or geochemical/diagenetic conditions varying on a seasonal or annual time scale (Foster, 1988). In view of the continuing debate on the processes of dolomitization and the lack of field data, this interpretation must be considered speculative. None of the other dolomitization models, recently reviewed by Tucker (1990) can presently be 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. 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 2,100 and 1,700 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 (Fig. 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).

Igneous Intrusions

One of the most characteristic features of the regional geology is its network of intersecting dikes (Fig. 2). There were at least three main episodes of dike emplacement (Day, 1980): Pilanesberg (1,310 ± 60 Ma), East Rand (1,120 ± 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 (2,096 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, found only 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 transported 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) recognize three distinct successive stages of dissolution of dolomite corresponding to three zones of rotten rock with a total thickness of about 10 cm. The incipient stage is evident as intergranular staining of carbonate crystals by oxides of iron and manganese and 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 a later 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, pseudomorphous after 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):

1. Pre-Pretoria period (about 2,250 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 paleosinkholes 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, mineralization with fluorspar, lead, and zinc has taken place. The unconformities within the Chuniespoort Group may also be considered palaeokarst horizons.

2. Pre-Waterberg period (about 1,700 Ma) - Outside the area under consideration, red sandstone correlated with Waterberg Group rocks has been observed infilling dissolution cavities.

3. Pre-Karoo period - This erosion period lasted about 1,300 Ma and includes Carboniferous continental glaciation. Drilling for geotechnical purposes, coal mining, and exploration for refractory clay deposits (e.g., Wilkins et al., 1987) 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 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.

4. 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, paleosinkholes have been infilled by red eolian sand and fluvial gravel, sand, and clay. The red sand is considered to be representative of Tertiary eolian 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 Fig. 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 100 m above the Chuniespoort Group outcrop (Fig. 9).

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 4.

1. The Plateau type 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 kilometers 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. The existence of sinuous ridge-like diamondiferous gravel deposits in the western Transvaal, which are the remains of palaeo-river courses, indicates that the present-day morphology has developed probably since the late Tertiary or Pleistocene. 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.

2. 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.

3. 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. Greater downcutting has occurred in this area. Valley floors are 150-200 m lower than in the adjacent dolomitic areas to the east and west. Caves are abundant and situated well above valley bottom level, 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 dikes cut the thalweg (Fig. 5).

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, Kleywegt and Enslin (1973) report that in this region leaching along tensional faults and fractures extends to depths of between 50 m and 200 m 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 also occur considerably deeper.

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.

A large number of caves owe their pattern to upward migrating 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 water table 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.

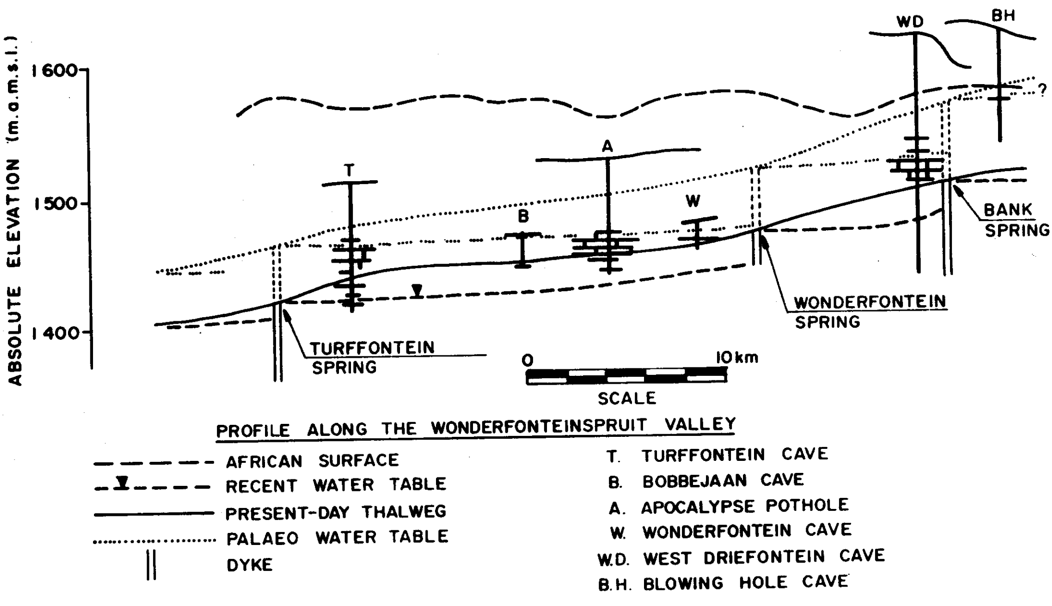


Figure 5. The effect of dikes on cave levels (after Martini et al., 1977).

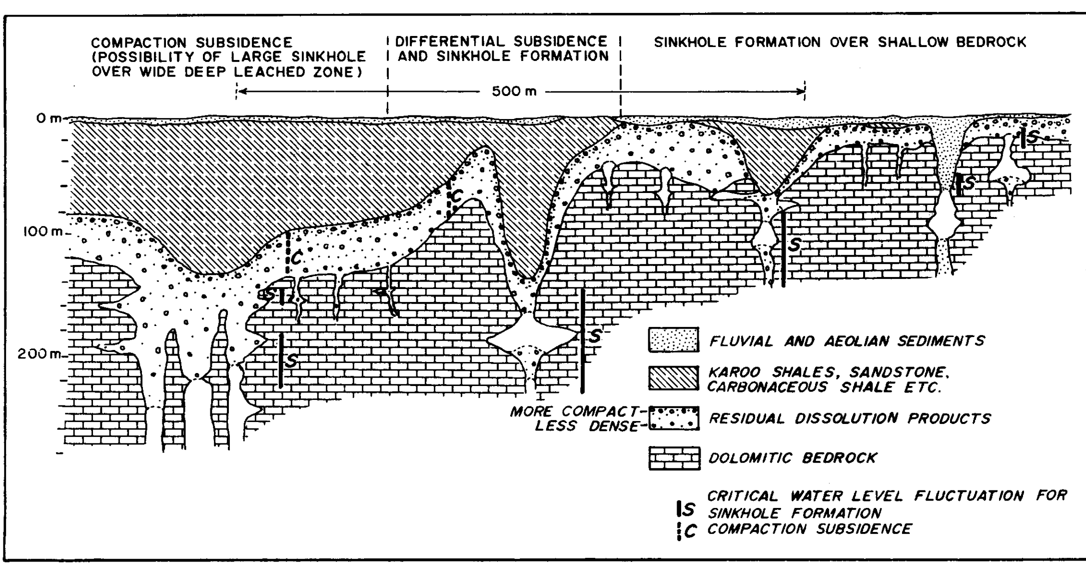


Figure 6. Semi-diagrammatic depiction of karst conditions on the Far West Rand illustrating presumed critical water-table fluctuation for compaction and sinkhole formation (after Kleywegt and Pike, 1982).

Present-day Sinkhole Formation and Subsidence

Over the past 30 to 40 years, human activities have led to a much accelerated rate of sinkhole formation and subsidence. These activities, principally urbanization 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 (e.g., Kleywegt and Enslin, 1973), and only the most important aspects are mentioned here.

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:

1. Abutments for the roof of a void provided by dolomite pinnacles or the sides of grikes.
2. Development of arching conditions in the residuum.
3. Development of a void below the arch.
4. A reservoir to accept material which is removed to enlarge the void and a means of transportation such as water.
5. A disturbance 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 6 illustrates the different conditions for the formation of sinkholes and compaction. 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

The present level of knowledge about the karst development in the Chuniespoort dolomitic strata is the result of field observations and the examination of caves, 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 (Table 1).

Lithostratigraphy

At the surface, the chert-free dolomite units weather forming karren or dolomite pavements (lapiez) 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.

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	2,850
Incompletely leached dolomite bedrock	2,600
Overburden material (surface deposits, wad, and incompletely leached dolomitic bedrock)	2,350
Karoo Sequence sediments	2,000-2,400
Surface deposits	1,600
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	2,100

These different weathering characteristics continue below the surface (Fig. 7). Ground-water exploration drilling south of Johannesburg showed that in the chert-rich formations water-bearing zones attained thicknesses up to 60 m. The considerable widening of the passages below chert ceilings, as depicted in Figure 7, have been described by Kent et al. (1975). The aquifer material in such zones has been described as very fractured and weathered chert, often with little evidence of any dolomite. 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 in discrete dissolution features in fresh dolomite. The dimensions of these features below water level are not known because air percussion drilling has failed to advance against conditions of air loss and high water pressure. Water strikes are commonly associated with thin bands of shale or chert.

Gravity anomaly maps in the Klip River Valley reveal zones of preferential weathering of the chert-rich Monte Christo and Eccles Formations and indicate that extensive zones of porous and permeable material form only where the weathering of closely spaced geological structures coalesce in these units. 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 (Fig. 7).

Palaeokarst

Throughout the south-central and western Transvaal, extensive dissolution is commonly found 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.

Intraformational episodes of karstification are now represented by unconformities. Several ground-water exploration boreholes obtained good water supplies after penetrating these horizons in excess of 200 m below ground surface, beneath extensive thicknesses of unweathered dolomitic strata. This effect could also be attributed to bedding-parallel structural features.

Tectonism and Igneous Intrusions

The control exerted by jointing and faulting upon karstification processes is evident from cave surveys (Fig. 8) as well as residual gravity maps. Kavalieris and Martini (1976) and Moon (1972) have shown the most important direction of cave passages west of the Halfway House dome to be east-west with another approximately perpendicular to it. Kavalieris and Martini (1976) 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 dikes. Others have associated the joint-controlled cave development to both older and more localized structural features (Partridge and Brink, 1965; 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 dike systems (Fig. 2). The dikes were intruded along lines of weakness caused by crustal tension. The strike-parallel system of joints and fissures has been extensively weathered forming linear zones of dissolution. The continuity of these linear zones of dissolution is often unaffected by lithostratigraphy. Exploratory drilling on the Far West Rand has confirmed dissolution channels in excess of 50 m wide. The hydrogeological characteristics of these zones are dependent upon the nature of the residual and transported material filling them. Some northwesterly and northeasterly trending features have been

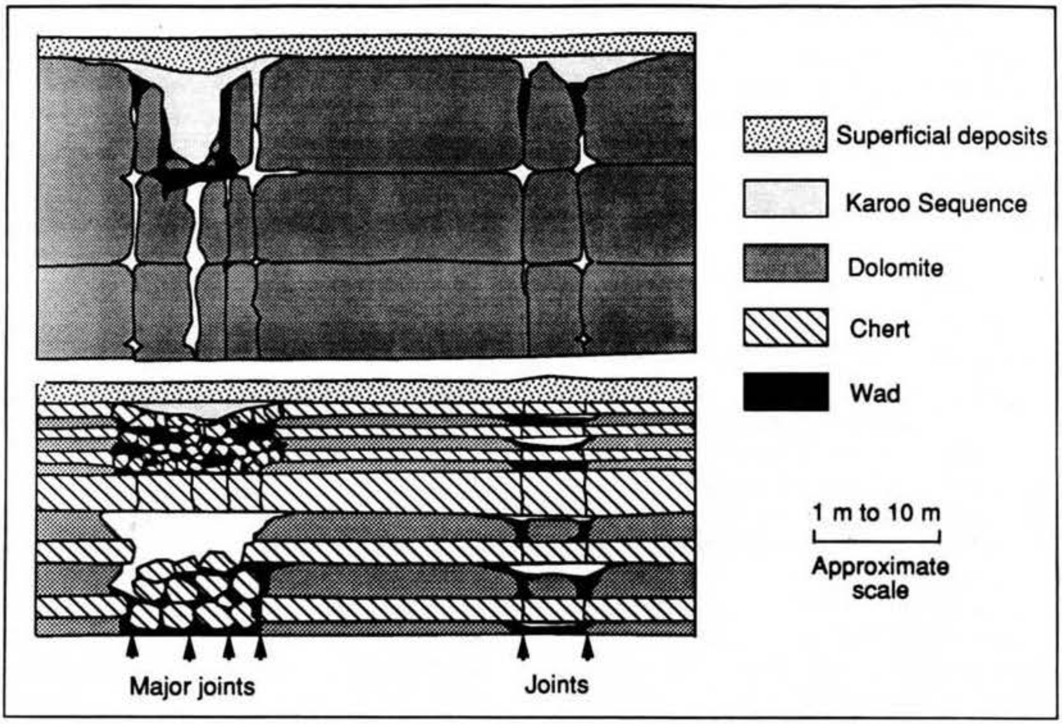
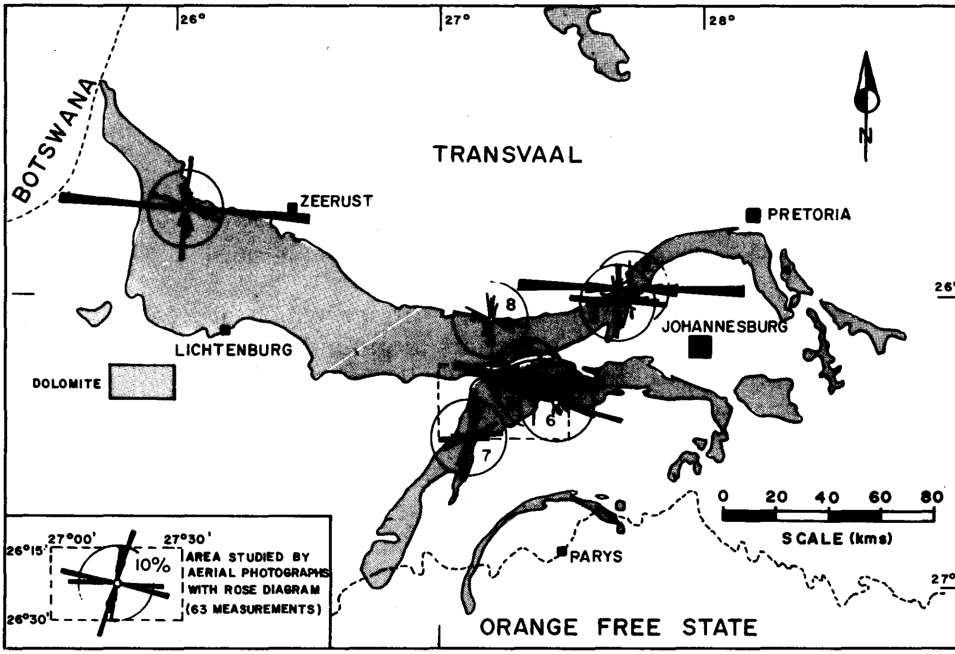


Figure 7. Sketch representation of weathering patterns in chert-poor and chert-rich dolomite (from Foster, 1988).



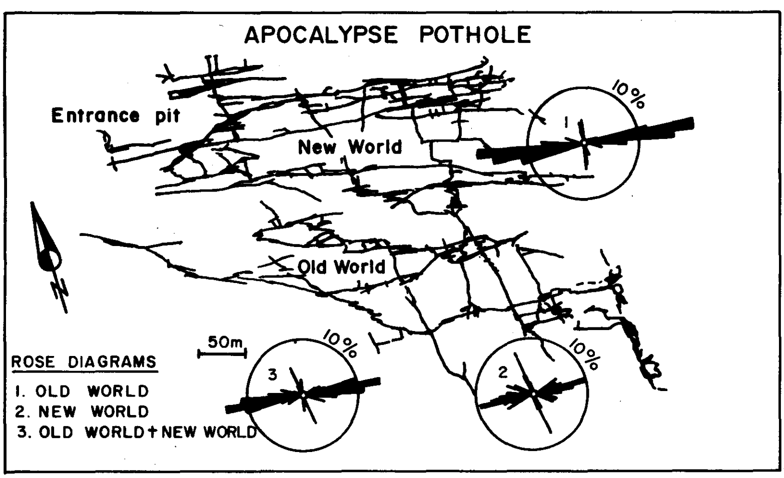


Figure 8. a) Strike of cave passages in south-central and western Transvaal (from Kavalieris and Martini, 1976); b) Strike of fissures in largest known cave in south-central and western Transvaal (from Kavalieris and Martini, 1976).

connected with faults encountered in gold mining. The complex pattern of crossing linear zones is evident on the gravity anomaly maps.

On the Far West Rand, a number of post-Transvaal tension faults of relatively small vertical displacement trend roughly parallel to the N-S Pilanesberg dike system and 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, is a powerful example of transmissive zones occurring to great depths. A low-angle normal fault was found to be the cause.

Discontinuities in the potentiometric surface which are usually observed across dikes indicate that they act as barriers to ground-water flow and divide the dolomitic strata into separate ground-water units or compartments (Figs. 2 and 5). Residual gravity data indicate that, in places, dike contact zones are favorable loci for dissolution of the dolomitic strata. 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-m thick post-Karoo dolerite sill have not yielded any water. 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.

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 9 is a semi-diagrammatic representation of hydrogeologic conditions in the Wonderfontein Valley.

As has already been mentioned, dikes have a profound influence on the hydrologic regime, by acting as 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 meters between adjacent compartments as a result. Surface or subsurface flow may occur between compartments. On the surface, water crosses the dikes after issuing as springs on the upstream side. Subsurface flow may occur at gaps in the dikes, where faults displace dikes, and where weathered and fractured dike rock extends to below the ground-water level.

Various 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 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 (Fleisher, 1981; Schwartz and

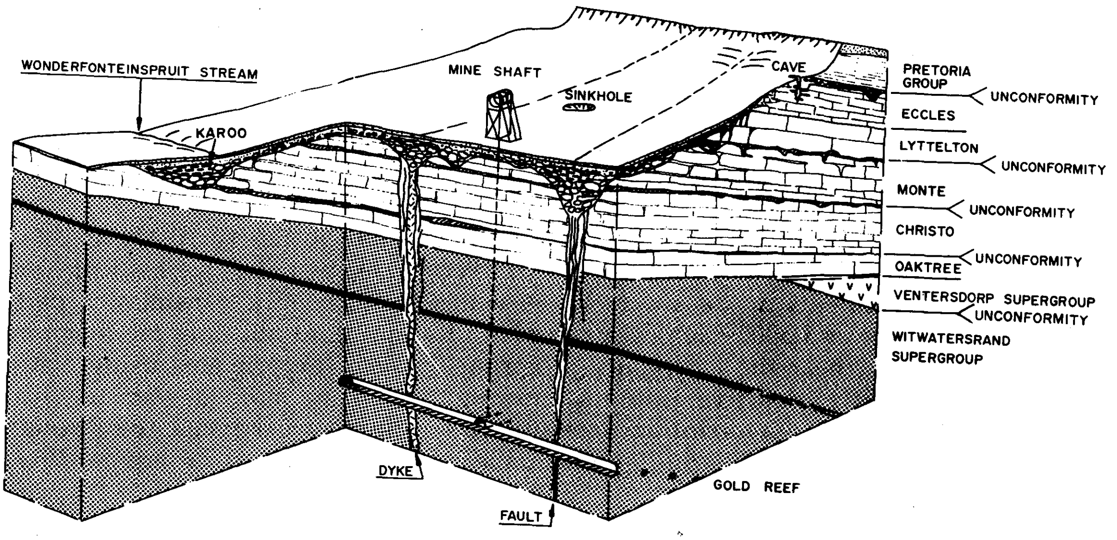


Figure 9. Schematic representation of aquifer conditions along the valley of the Wonderfonteinspruit Stream.

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%. 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 range from as high as 14% at the water table to less than 2% at 150 m below the surface (Foster, 1987).

Transmissivities range from less than 10 m^2/day to nearly 30,000 m^2/day (Schwartz and Midgley, 1975; Fleisher, 1981). 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 m deep, water recharged through boreholes at the surface could enter mine workings within 24 hours (West Driefontein Mine, pers. comm.).

HYDROLOGY

Most springs issue on or near the contacts with dikes, the underlying quartzitic Black Reef Formation, or 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 0.001 to about 3 m^3/s (greatest flow at Schoonspruit Spring). The more important springs have fairly constant flows which do not deviate by more than 40 to 65% 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 annual 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 (Fig. 10a).

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 (Fig. 10b). Similar fluctuations of the piezometric level have been observed in the Wondergat sinkhole in the western Transvaal and elsewhere (Fig. 10c). This phenomenon can be ascribed to the delayed recharge as well as limited outflow at the springs.

Ground-water replenishment by rainfall in compartments lacking surface streams has been estimated by means of water balances and other methods. Mean

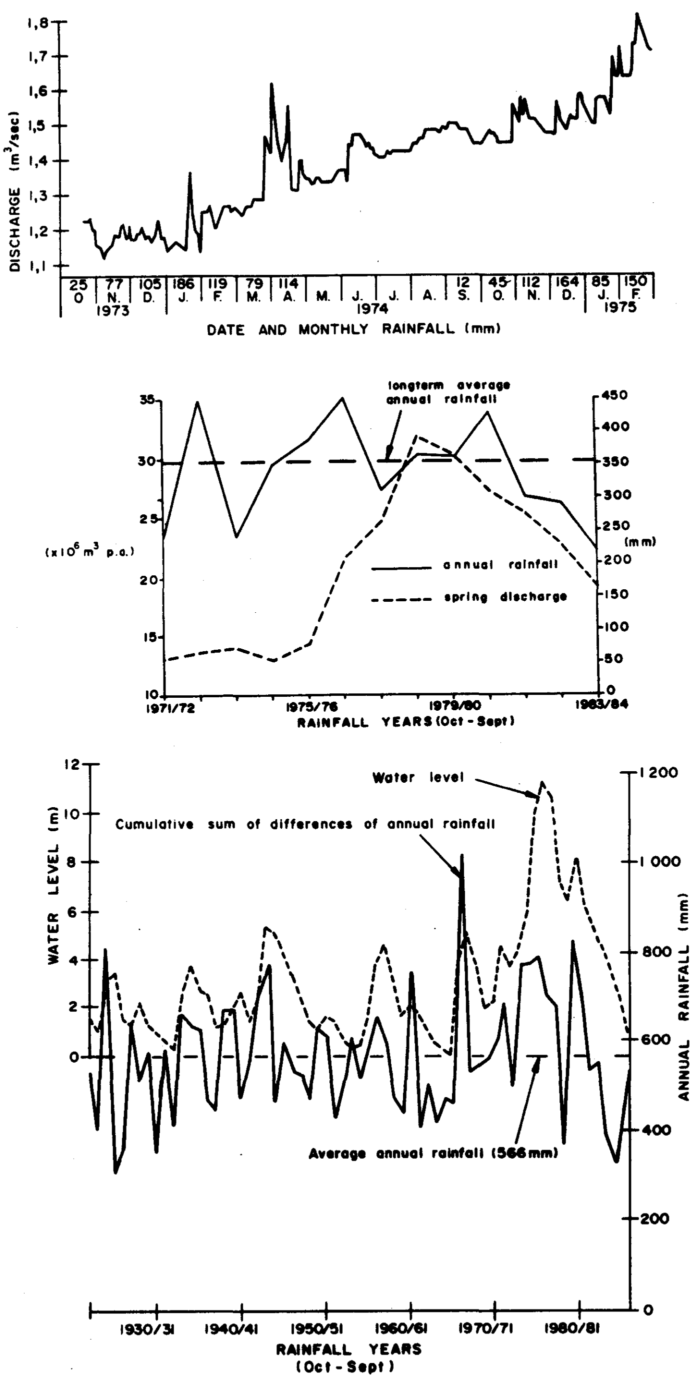


Figure 10. a) Schoonspruit Spring discharge hydrograph showing immediate summer rainfall recharge and continued recharge in winter months (after Fleisher, 1981); b) Maloney's Eye discharge hydrograph showing long-term response to exceptionally high rainfall years; c) Wondergat water-level fluctuations in response to high rainfall years.

annual recharge has been found to range from 60 mm in the west to about 110 mm in the east. The ratios of storage to mean annual recharge (Table 2) reveal that total aquifer storage is generally much greater than the annual recharge and also indicate that maximum aquifer through-flow 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) (C=B/A)	Mean annual recharge (mm) (D)	Storage/ Mean annual recharge (C/D)
Grootfontein (Western Transvaal)	128	220	1.7	70	25
Venterspost (Far West Rand)	54	460	8.5	85	100
Oberholzer (Far West Rand)	150	1,050	7.0	85	82

CONCLUSIONS

Varying depositional and diagenetic environments in the Precambrian resulted in dolomitic formations with fundamentally different weathering characteristics. Unimpeded downward percolation of aggressive ground water 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), 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, during Chuniespoort sedimentation as well as in subsequent periods, have affected the whole of the Transvaal Basin.

Although extensive erosion surfaces form major elements of today's southern African landscape, karst erosion levels are locally determined by the level of erosion of the dikes which form ground-water barriers. The retardation of the ground-water flow by the dikes 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.

Tectonism is responsible for the creation of the joints and fissures essential for karst erosion to take place in ancient carbonate rocks. Throughout the south-central and western Transvaal, folds, faults, major joints, dikes, and sills have all been found to be associated with zones of greater dissolution and, hence, greater transmissivities and storativities. Not one of these tectonic features dominates karst development. In any given area, there is normally one dominant structural or intrusive feature associated with the greatest development of karst.

Lithostratigraphy, palaeokarst history, tectonics, and the network of intersecting dikes are the major controls on the development of the karst aquifer in the Chuniespoort Group. Knowledge of these subjects is therefore crucial for an understanding of the hydrogeology of this karst region.

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