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# SURFACE SUBSIDENCE AND SINKHOLES CAUSED BY LOWERING OF THE DOLOMITIC WATER-TABLE ON THE FAR WEST RAND GOLD FIELD OF SOUTH AFRICA

*by*

R.J. KLEYWEGT, Ph.D. and D.R. PIKE, M.Sc.


## *Abstract*

Gold produced by the thirteen mines on the Far West Rand Gold Field contributes significantly to the South African economy. Most of the mines lie within the three dolomitic groundwater compartments which are being dewatered for economic and safety reasons following approval by the State. Lowering of the water-table began in 1957 and ground subsidences and sinkholes have occurred on a relatively large scale since then. Two organizations were formed, one by the State and the other by the mining industry (Chamber of Mines of South Africa) to protect the interests of the public. The first was to undertake the necessary research and exploratory investigations so as to be able to advise the public on the stability or otherwise of properties for development or future occupation. The second was to deal with all claims resulting from decisions taken by the first organization. These two organizations were mainly responsible for restoring confidence in the development of the area, which had sunk to a low ebb when the spate of sinkholes and subsidences first occurred during the early 1960s.

A brief account is given of the regional and local geology and geohydrology and their relationship to the formation of sinkholes and the occurrence of ground subsidences. The mechanism, temporal and spatial extent and the nature of the ground subsidence are described as is the delineation of areas of potential subsidence by gravity surveys.

Most sinkholes have occurred in low-lying areas where the water-table was originally close to the surface. Some larger ones occurred in high ground, where it is believed that leaching along fault and fracture zones in an alternation of dolomite and chert produced relatively narrow, deep caverns into which the overburden eventually collapsed due to infiltration of abnormal amounts of surface water and severe mine tremors. Elsewhere rejuvenation of filled Quaternary palaeo-sinkholes has compounded the problem and it has been established that these ancient fillings are sensitive to large temporary fluctuations of the water-table.


## 1. INTRODUCTION

### 1.1 ECONOMIC IMPORTANCE OF THE AREA

The gold produced by the Far West Rand gold mines in 1972 totalled almost 20 per cent of published world production and was valued at nearly US $500 million at the official price of US $42,22 per ounce (Kleywegt and Enslin 1973). Bezuidenhout and Enslin (1969) estimated that some 6 million kilograms of gold still remained to be mined, and this has been augmented by one medium and two large mines which have since come into operation.

### 1.2 GOLD MINING IN THE AREA

The thirteen Far West Rand gold mines are located in an area of some 850 km$^2$ with an east–west dimension roughly three times the north–south dimension (Fig. 1.1). Most of the

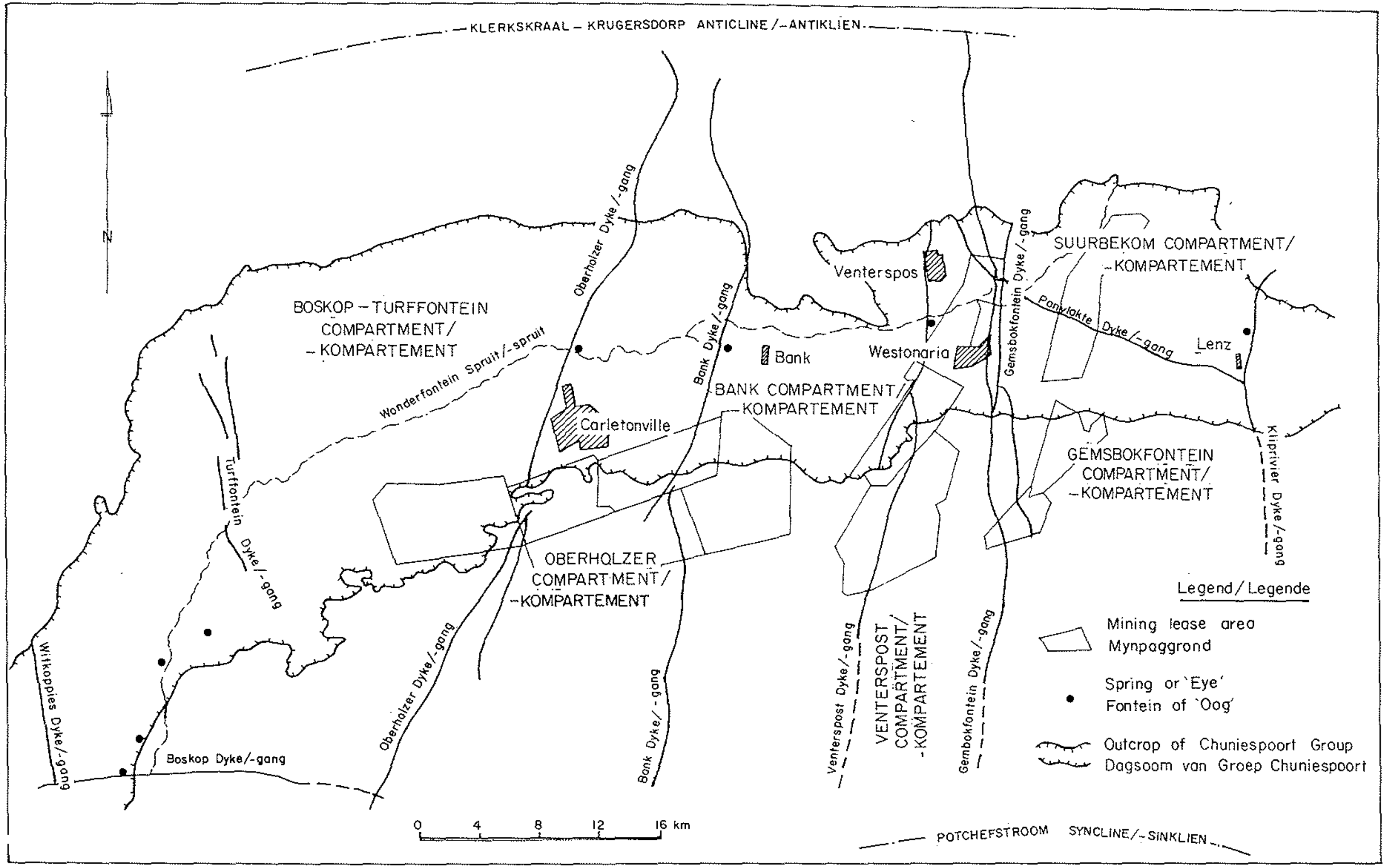



Fig. 1.1 – Far West Rand Dolomitic Area. Bank and Venterspost Compartments are being dewatered (after Enslin et al. 1976 *in* IAHS Publication 121, Fig. 2).
*Verre Wes-Rand Dolomitiese Gebied. Bank- en Venterspostkompartemente word ontwater (volgens Enslin et al. 1976* in *IAHS-publikasie 121, Fig. 2).*

installations, particularly at the older mines, are situated on dolomite of the Chuniespoort Group in which a broad valley has been carved and which is drained by the Wonderfontein Spruit.

Extensive near-surface dissolution of the dolomitic formations, associated essentially with fracture systems, has turned the Chuniespoort Group into an important aquifer. In 1912 the development of the Pullinger shaft near Westonaria was finally stopped by an inflow of dolomitic groundwater estimated at 22 Mℓ/d (Borchers 1964). It was not until the mid-1930s when larger pumping capacities could be provided and the cementation process effectively used that the underlying gold-bearing strata, the presence of which had been established during a highly successful prospecting programme (Krahmann 1936), could be mined.

The vast overlying dolomitic aquifer has both economic and safety implications to the mines because of the pumping costs involved and the hazard of possible large uncontrollable inrushes of water into the mine workings. Bezuidenhout and Enslin (1969) for example, mentioned the 365-Mℓ/d inrush into the West Driefontein Mine in October 1968 and the outstanding achievement of evacuating the labour force without loss of life, and eventually saving the mine. The epic story has been fully told by Cartwright (1969).

### 1.3 DISPOSAL OF PUMPED MINE WATER

In the final report to the Minister of Water Affairs an interdepartmental committee which investigated the disposal of pumped mine water, recommended that, considering the life-span of the mines operating in the Venterspost and Oberholzer Dolomitic Groundwater Compartments, it would be more economic to dispose of the pumped water beyond the confines of the compartments than to recirculate it and that the consequent draw-down of the water-table would make the mining operations less hazardous. In 1964 it was estimated that, considering the life-span of the mines, the saving in pumping costs would probably exceed R500 million (US $ 700 million).

The committee also recommended that the mining companies should be required to compensate for any damage which might result from differential subsidence and sinkholes which could be attributed to the dewatering.

### 1.4 LOWERING OF THE WATER-TABLE AND CONSEQUENT EFFECTS

In 1960 the water-table in parts of the two compartments being mined was already being lowered and in addition to private boreholes drying up the first signs of slow ground subsidence were in evidence and several sinkholes had occurred, particularly in the low-lying areas of the Venterspost Compartment.

In the Oberholzer Compartment ground movement was most severe during 1962, as is reflected by the number of essential municipal services which had to be repaired (Fig. 1.2), while sinkholes occurred sporadically, again mostly in the low-lying areas. When in December 1962, however, a crusher plant on the West Driefontein Mine property was engulfed in a sinkhole (Pl. 1.1) with the loss of 29 lives, the need for delineating all ground which could subside and areas in which sinkholes could form became a matter of great urgency. Work for this purpose was at that time being undertaken on an ad-hoc basis by the mining companies in the area and by the Geological Survey on behalf of the State, Provincial and Municipal authorities. In addition the Chamber of Mines was financing projects aimed at finding a suitable geophysical technique or techniques for locating voids or underground conditions which might lead to the formation of sinkholes.

### 1.5 IMPLEMENTATION OF THE POLICY OF DEWATERING

The policy of dewatering was finally accepted in 1964 when the necessary permits were issued following discussions and agreement between the State and the Chamber of Mines regarding the need to compensate parties for damage to properties occurring as a direct result of the act of dewatering. In order to implement the provisions in the agreement, two bodies were formed, financed by the State and the Chamber of Mines respectively. They were:

1. The State Technical Co-ordinating Committee on Sinkholes and Subsidences on the Far West Rand, which collects all available information and conducts all the necessary research and routine surveys so as to be able to advise the public and all interested parties on the suitability of ground for development, and determine, for compensation purposes, the cause of subsidences and sinkholes which result in damage to property.

2. The Far West Rand Dolomitic Water Association, which deals with all claims for compensation for damage certified by the State Technical Committee to be the direct physical result of dewatering.

### 1.6 COSTS OF DEWATERING

Bezuidenhout and Enslin (1969) stated that "the direct expenditure in research, application of safety measures, compensation for damage or loss of water supplies and the rebuilding of mining plants on safe areas, has been estimated at R25 million". This amount should be compared with the estimated saving in pumping costs given in 1.3.

## 2. GEOLOGICAL SETTING

### 2.1 PREVIOUS DESCRIPTIONS

The geological and geohydrological setting of the Far West Rand Gold Field has been described by De Kock (1964), Bezuidenhout and Enslin (1969) and Kleywegt and Enslin (1973).

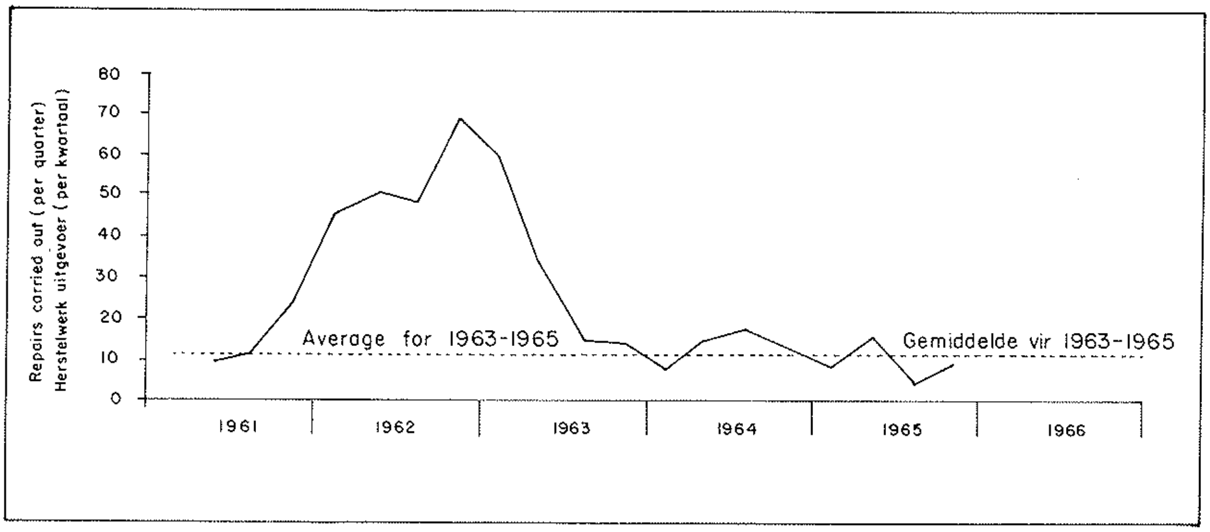
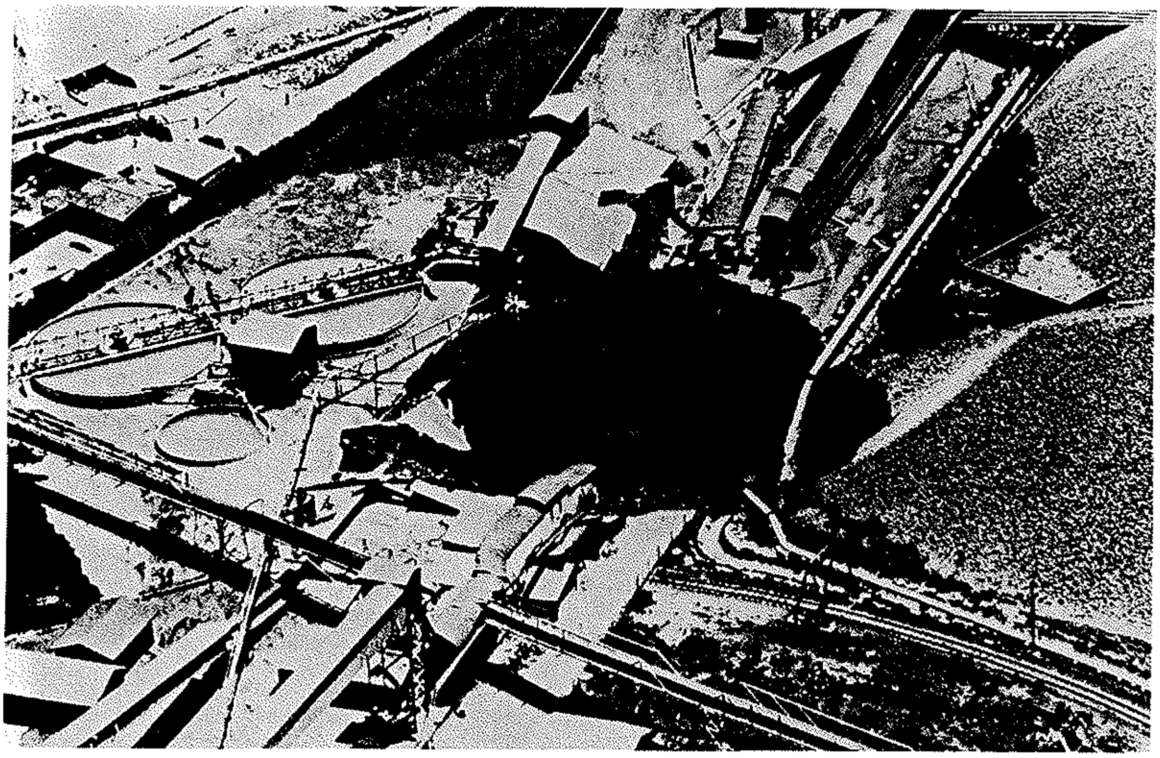



Fig. 1.2 — Repairs to essential services in Carletonville, 1961—1965 (after Die Staats- Koördinerende Tegniese Komitee insake Sinkgate en Insakkings 1966, Suid-Afrika).
*Herstelwerk aan noodsaaklike dienste in Carletonville, 1961—1965 (volgens Die Staats- Koördinerende Tegniese Komitee insake Sinkgate en Insakkings 1966, Suid-Afrika).*



Pl. 1.1 — Sinkhole at crusher plant, West Driefontein Gold Mine (with acknowledgement to IAHS Publication 89, Pl. 1).
*Sinkgat by klipbreekinstallasie, Wes-Driefonteingoudmyn (met erkenning aan IAHS-publikasie 89, Pl. 1).*

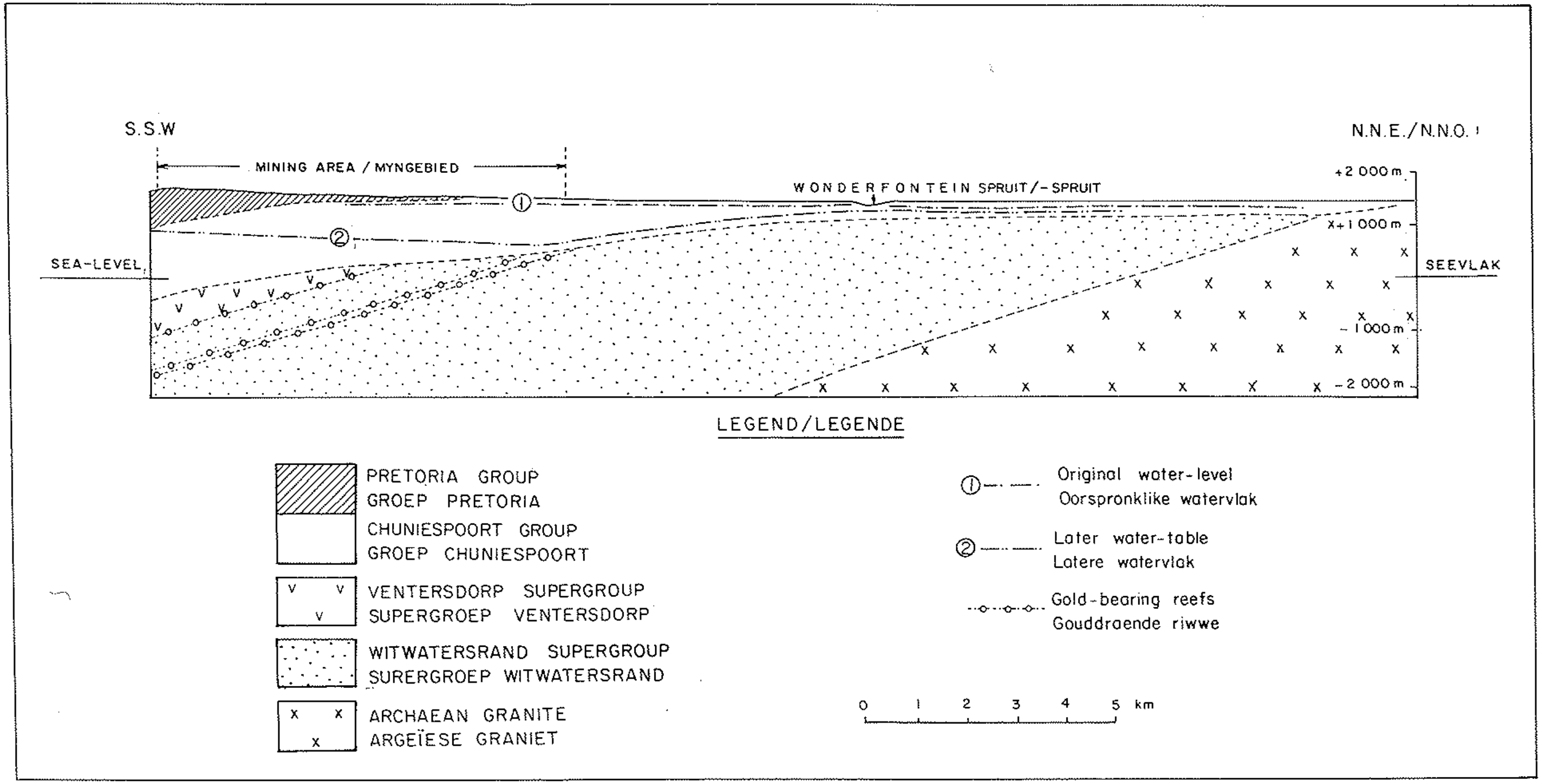



Fig. 2.1 — Schematic geological cross-section of the Far West Rand Gold Field (after Enslin et al. 1976, *in* IAHS Publication 121, Fig. 1).
*Skematiese geologiese dwarssnit van die Verre Wes-Randgoudveld (volgens Enslin et al. 1976,* in *IAHS-publikasie 121, Fig. 1).*

## 2.2 REGIONAL GEOLOGY

The gold field is located along the flank linking the Klerkskraal–Krugersdorp anticline to the north and the Potchefstroom syncline to the south (Fig. 1.1). The gold is contained in conglomerates of the Witwatersrand Supergroup and the Ventersdorp Contact Reef of the Ventersdorp Supergroup beneath the Transvaal Sequence (2 000 to 2 300 Ma) which dips regionally in a southerly direction at about 6° to 12° and which comprises the Black Reef Quartzite Formation (6 to 30 m), overlain in turn by the Chuniespoort Group (1 200 m) and the Pretoria Group (2 700 m) as shown in Figure 2.1.

## 2.3 NEAR-SURFACE GEOLOGY

The dolomitic limestones of the Chuniespoort Group are mostly concealed by an overburden made up of a dolomitic residuum of clay and the insoluble oxides of manganese and iron through which are distributed, in generally irregular fashion, blocks and fragments of chert of all possible sizes.

Outliers of the Ecca Group (Karoo Sequence) comprising coal, carbonaceous shale, shale, clay and sandstone and/or Quaternary gravel, sand and clayey sand complete the succession.

In a normal succession the age and degree of compaction of the in-situ dolomitic residuum increases from the dolomitic bedrock upwards. It changes progressively from a very low bearing capacity, highly porous mass of clayey manganese oxides, known as wad, and residual chert through a mixture of chert and manganese oxides, becoming progressively more compact as a result of the longer period of compaction by the overlying materials, to a compact chert breccia cemented by manganese and iron oxides (Kleywegt and Enslin 1973).

In the upper portion of the Chuniespoort Group the number of chert intercalations in the dolomitic limestones increases to about 20 per cent and this is mostly followed by a chert breccia known as the Giant Chert, with a thickness of 6 to 63 m (De Kock 1964).

## 2.4 TECTONICS AND ITS EFFECTS

A number of widely spaced post-Transvaal tensional faults and fractures of fairly limited displacement (De Kock 1964) have promoted the leaching of dolomitic limestones to greater depths than in the intervening areas where the dolomitic bedrock is normally within 15 m of the original water-level, as a result of the easier circulation of groundwater. In Karoo times this preferential leaching allowed the formation - by the accumulation of the appropriate materials and their settlement as compaction of the leached materials proceeded - of up to 30 m of coal and carbonaceous shale in linear zones up to a maximum of 700 m wide. This cycle of deposition was followed by the deposition of a widespread blanket of light-coloured shale and clay. The Karoo rocks have been stripped almost entirely in the vicinity of the Wonderfontein Valley (Kleywegt and Enslin 1973).

Significant leaching of the dolomitic limestones over the post-Transvaal tensional faults and fractures may extend to depths of 100 m below the level of the original water-table but beneath this level it is normally confined to joints (Enslin et al. 1976).

Below the Giant Chert horizon, leaching from vertical fractures laterally along sub-horizontal planes yields a particularly cavernous condition in which the rigid insoluble intercalated layers of chert act as a bridging medium.

# 3. GEOHYDROLOGY

## 3.1 PREVIOUS DESCRIPTIONS

The supplies of groundwater in the Chuniespoort Group in the Transvaal were reported on by Enslin (1967) and Enslin and Kriel (1967).

## 3.2 DOLOMITIC GROUNDWATER COMPARTMENT

The area is traversed by a number of impervious, near-vertical dykes, about 6 to 60 m thick and trending north–south (De Kock 1964) which divide the formations and particularly the dolomite into groundwater compartments (Figs 1.1, 3.1 and 3.2). The compartments in the gold-mining area discharge westwards and are the Gemsbokfontein, Venterspost (and Venterspost Subcompartment), Bank, Oberholzer and the Boskop–Turffontein Compartments. Dewatering of the Venterspost and Oberholzer Compartments commenced in the late 1950s and that of the Bank Compartment in 1970.

## 3.3 STORAGE OF GROUNDWATER

Before dewatering the overflow from one compartment to the next occurred at the lowest point of the relevant dyke, where water emerged as a spring (Figs 1.1 and 3.2). The average quantities discharged from spring to spring increased from about 8,6 Mℓ/d in the east at the Gemsbokfontein "eye" to 54 Mℓ/d at the Oberholzer "eye" in the west (Enslin 1967).

Most of the groundwater is stored in the overburden and in the highly leached zones over the faults and fractures (Enslin et al. 1976). In the areas between the highly leached zones the dolomitic bedrock lies on average about 10 to 15 m below the original water-table in the easternmost compartment, but the relationship changes progressively until in the westernmost compartment it is normally above this level (compare the situations in Figs 3.3 and 3.4 which are geological profiles in the Venterspost and Oberholzer Compartments respectively). In the easternmost compartments water is, therefore, also stored in the overburden over the relatively shallow dolomitic bedrock while in

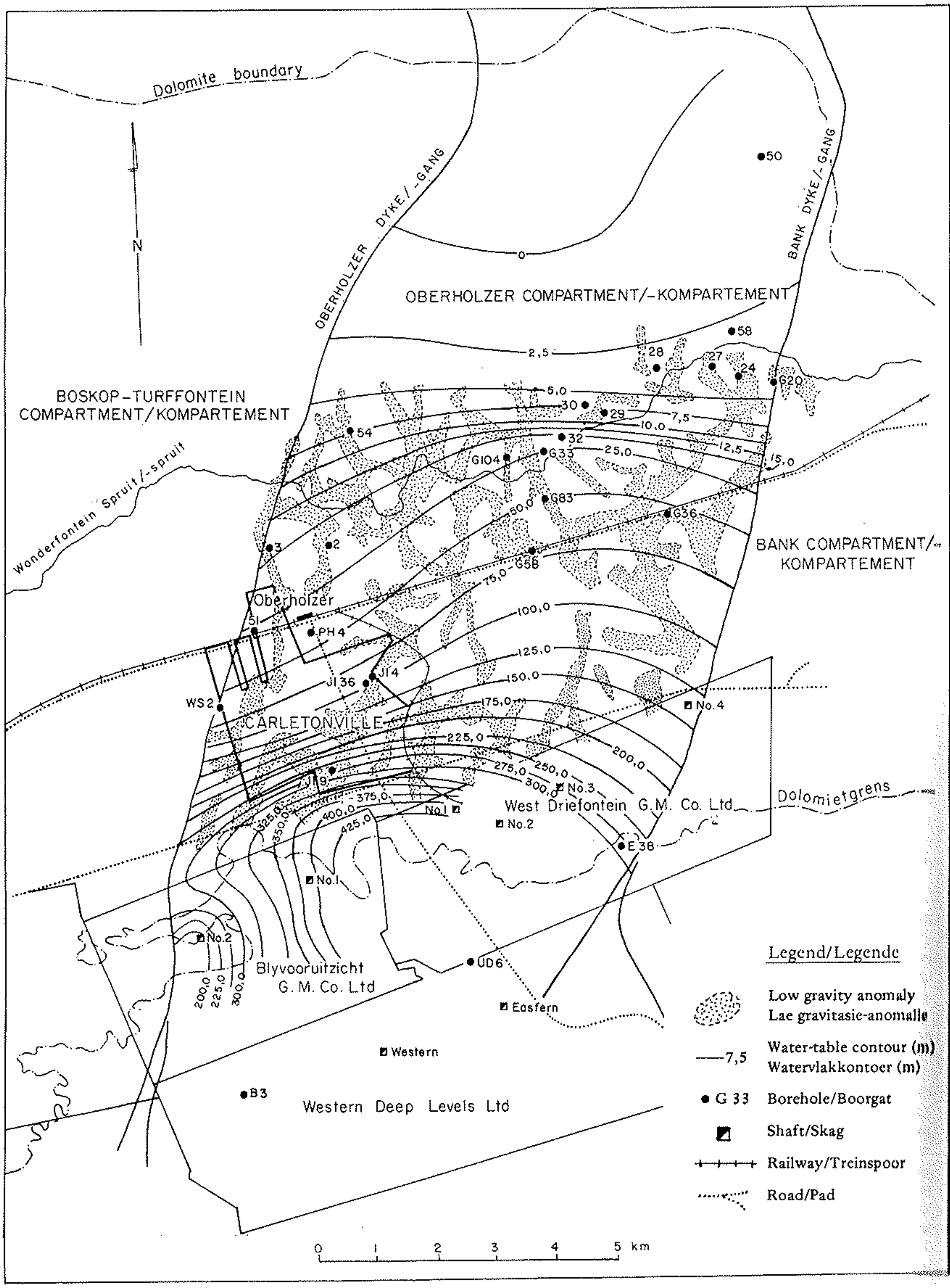



Fig. 3.1 – Water-level draw-down in 1965 (contours) and gravity low areas (shaded) in the main dolomitic aquifer in the Oberholzer Compartment (after Die Staats- Koördinerende Tegniese Komitee insake Sinkgate en Insakkings 1966, Suid-Afrika).
*Watervlaksakking in 1965 (kontoere) en gravitasielaaggebiede (gearseerd) in die hoof- dolomitiese waterdraer in die Oberholzerkompartement (volgens Die Staats- Koördinerende Tegniese Komitee insake Sinkgate en Insakkings 1966, Suid-Afrika).*

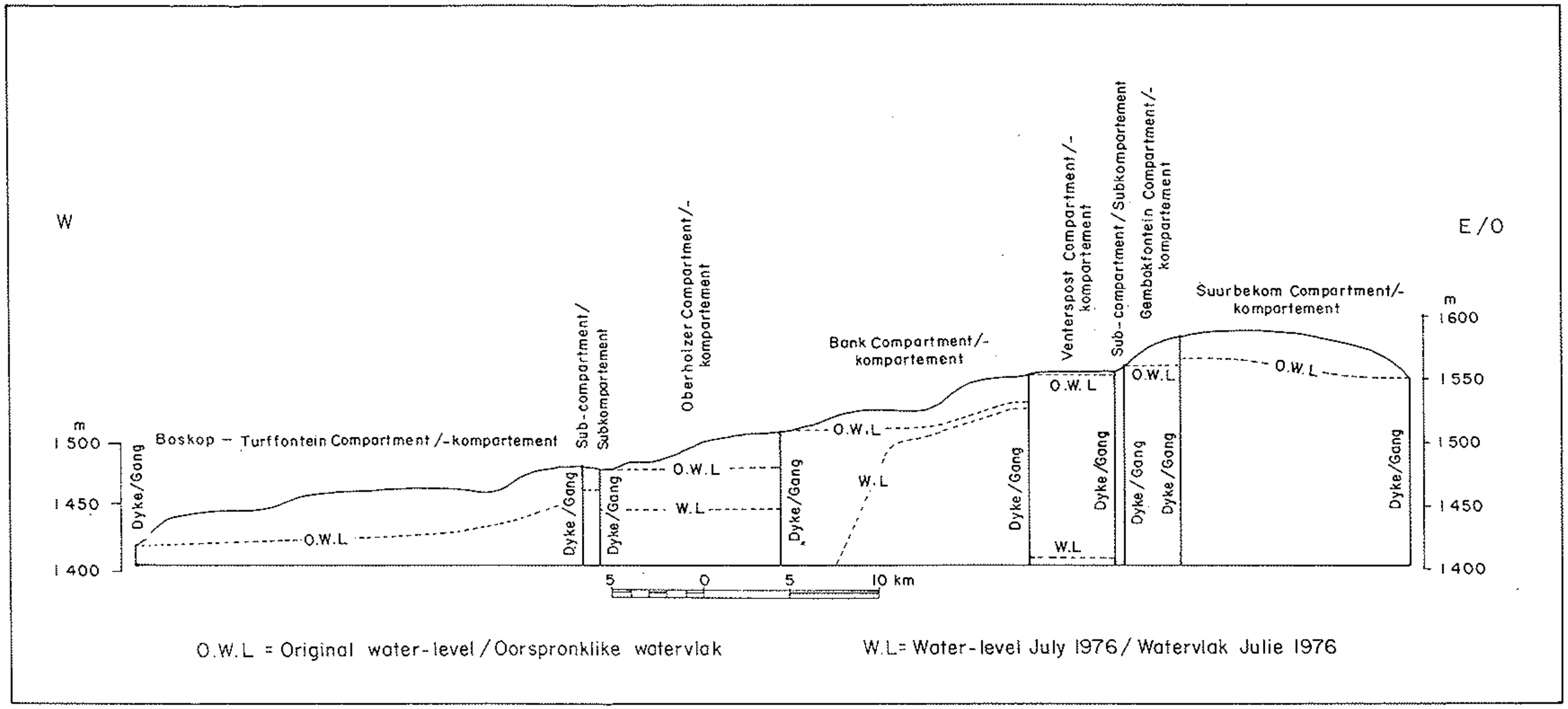



Fig. 3.2 – Longitudinal groundwater section along the Wonderfontein Spruit, Far West Rand (after Enslin et al. 1976, *in* IAHS Publication 121, Fig. 2).
*Oorlangse grondwatersnit langs die Wonderfonteinspruit, Verre Wes-Rand (volgens Enslin et al. 1976,* in *IAHS-publikasie 121, Fig. 2).*

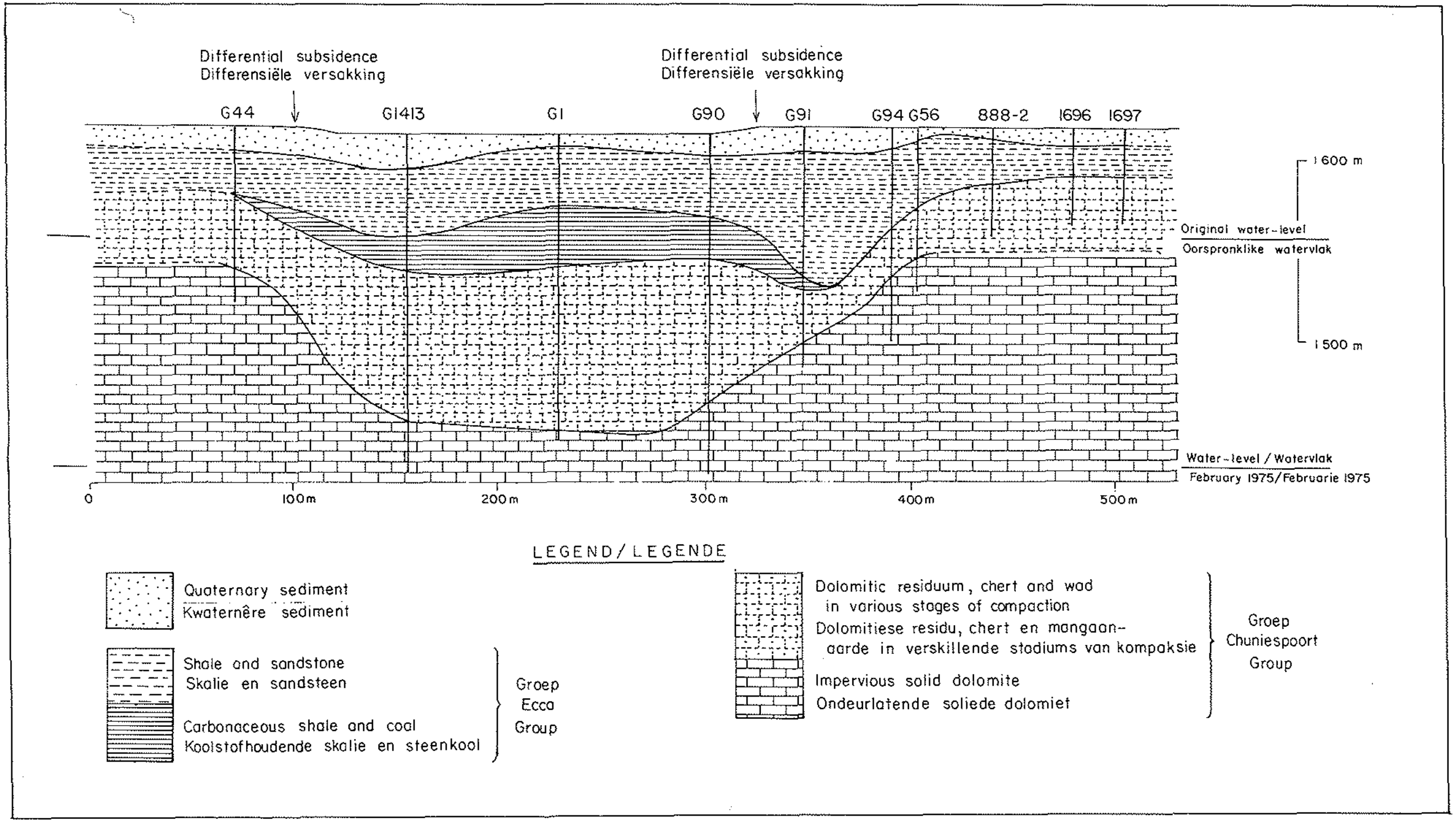



Fig. 3.3 – Geological profile across the main gravity low in Westonaria, Venterspost Compartment (Geological Survey of South Africa).
*Geologiese snit oor die hoofgravitasielaag in Westonaria, Venterspostkompartement (Geologiese Opname van Suid-Afrika).*

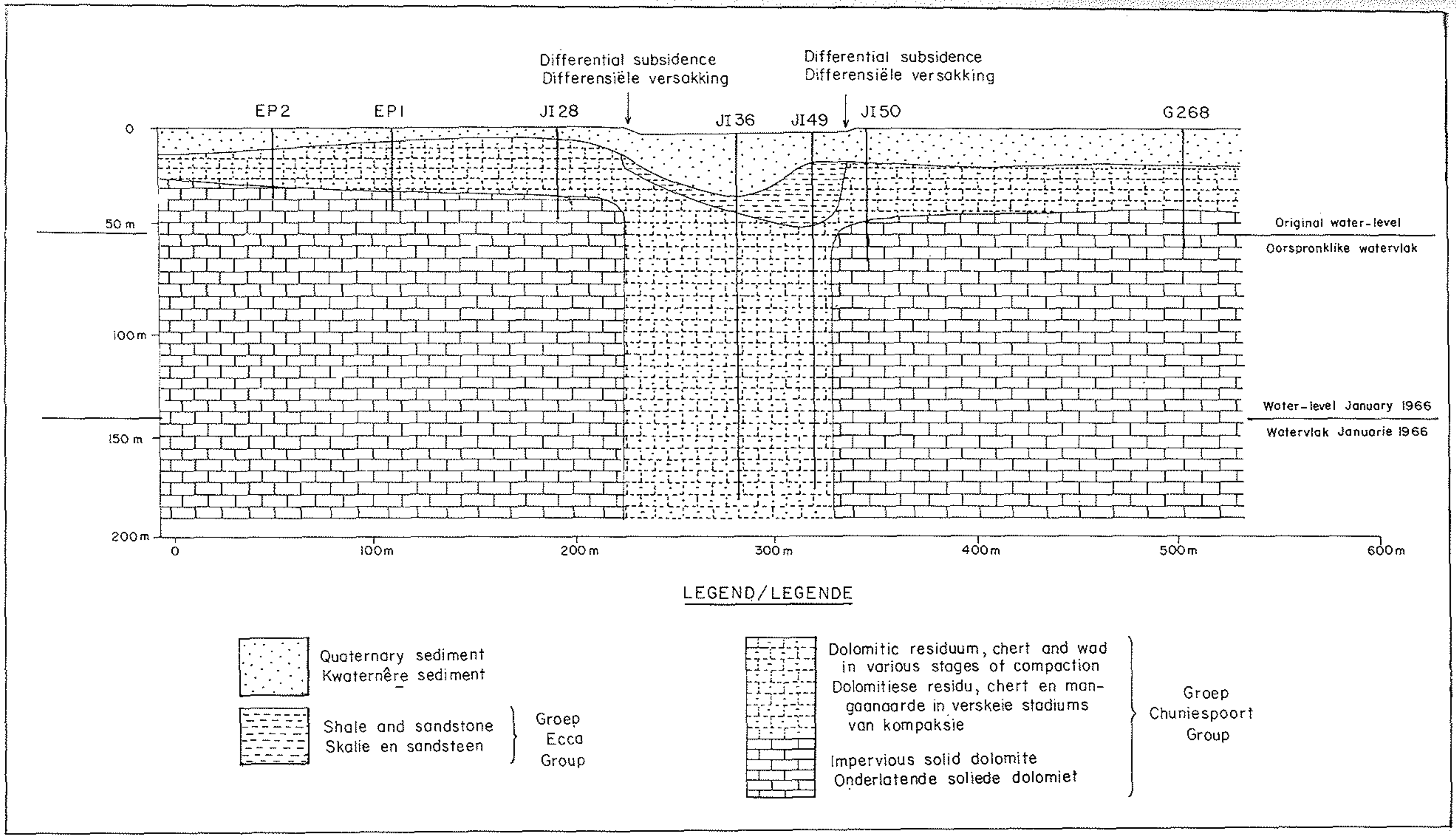



Fig. 3.4 — Geological profile across the Kernite Street gravity low in Carletonville, Oberholzer Compartment (after Die Staats- Koördinerende Tegniese Komitee insake Sinkgate en Insakkings 1966, Suid-Afrika).
*Geologiese snit oor die Kernitestraat-gravitasielaag in Carletonville, Oberholzerkompartment (volgens Die Staats- Koördinerende Tegniese Komitee insake Sinkgate en Insakkings 1966, Suid-Afrika).*

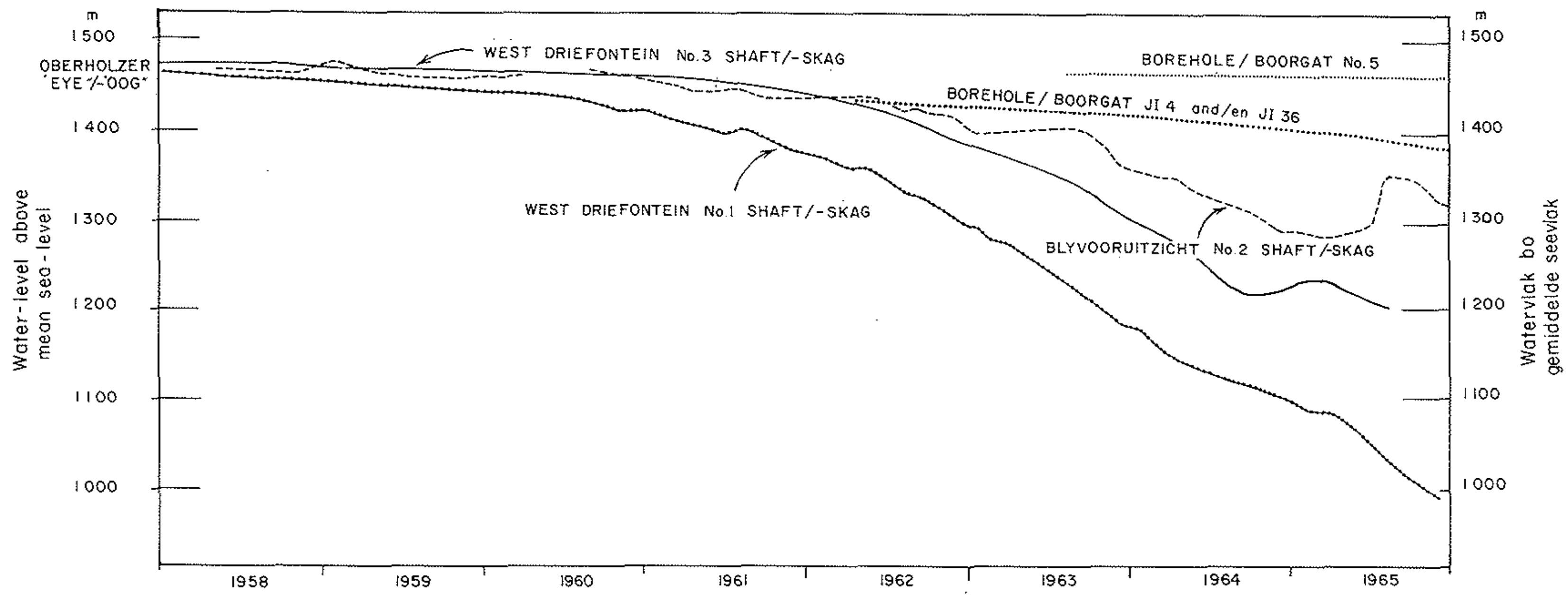



Fig. 3.5 — Lowering of the water-level in shafts and boreholes in the Oberholzer Compartment, 1958–1965 (after Die Staats- Koördinerende Tegniese Komitee insake Sinkgate en Insakkings 1966, Suid-Afrika).

*Verlaging van die watervlak in skagte en boorgate in die Oberholzerkompartement, 1958–1965 (volgens Die Staats- Koördinerende Tegniese Komitee insake Sinkgate en Insakkings 1966, Suid-Afrika).*

the west it is stored almost exclusively in the highly leached fracture zones. Due to the nature of the leaching most of the water stored in the main dolomitic aquifer occurs in the first 100 m below the water-level. De Kock (1964) estimated the storage capacity of the first 30 m to be about 10 per cent, the next 30 m about 2 per cent and below that, considerably less than one per cent. Brink and Partridge (1965) quoted a similar pattern from unpublished work done by Knight, while contributors to the Interdepartmental Report of the Director of Water Affairs (1960) suggested 15 per cent to a depth of 30 m and 1,5 per cent below this to 150 m.

### 3.4 WATER-TABLE DRAW-DOWN

Although the secondary permeability of the dolomitic limestones is strongly developed, they decrease sharply in water-bearing capacity downwards and it is very difficult to follow the falling water-table deeper than about 100 m below original level except at some mine shafts. Bezuidenhout and Enslin's (1969) Figure 6 showing the lowering of the groundwater-table in some boreholes and shafts in the Oberholzer Compartment is reproduced here in modified form as Figure 3.5. The plan of water-table draw-down in the same compartment (Fig. 3.1) is a modified version of a figure from the State Technical Committee's unpublished report (1966). The latter figure also shows all the major gravity-low features, most of which reflect the important leaching and, hence, water-bearing zones in the compartment. These may comprise some 10 to 20 per cent of the compartments. Fortunately most of the movement recorded has been confined to the area affected by draw-down of up to 100 m.

### 3.5 GEOHYDROLOGICAL PARAMETERS

Because of the high permeability of the lowermost, completely leached zones, the gradient of the water-table in the compartments is usually very low - between 1:500 and 1:5 000 (Director of Water Affairs 1960). A typical geohydrological section along the Wonderfontein Valley and a cross section of the Oberholzer Compartment were given by Enslin et al. (1976) and are reproduced here as Figures 3.2 and 2.1 respectively.

## 4. MECHANISM OF GROUND MOVEMENT IN THIS DOLOMITIC ENVIRONMENT

### 4.1 DOLOMITIC BEDROCK SURFACE

From the combined evidence afforded by about 4 000 holes drilled to bedrock, shaft sinking and gravity data it is obvious that the interface between dolomitic bedrock and the overlying formations (also referred to as overburden) is very uneven. There is in fact no reason to distinguish its morphology from that of much of the karst which is exposed to the atmosphere at the present time and which exhibits characteristics known all over the world. In addition to the unevenness of the rock surface there are extensive systems of cavities and cavernous conditions in the rock, some of which have been mapped and shown to be the network of openings resulting from selective phreatic dissolution along joints, in one case 10,8 km in total extent (Martini and Kavalieris 1976).

### 4.2 PHYSICAL CHARACTER OF OVERBURDEN

A strong impression is also gained of a very heterogeneous overburden bearing upon the typically rough and dissected karstic bedrock surface, containing irregularly distributed voids of various sizes above, and in, partly filled fissures in the bedrock. Like the cavities and cavernous conditions in the bedrock, these voids are capable of accepting overburden materials in a variety of sizes and at different rates. The portion of the dolomitic residuum immediately overlying the bedrock is usually very, if not completely, leached and consists mostly of an extremely porous lattice work of silica and finely divided oxides of manganese and iron (wad) of density around 500 kg/m$^3$ and disaggregated grains of dolomite (Martini and Kavalieris 1976). This material, when removed from its environments and tested by itself, has virtually no mechanical strength, bearing capacity or cohesion.

### 4.3 METASTABILITY IN OVERBURDEN

From the evidence it is clear that a strong correlation exists between the onset of instability at the ground surface, and withdrawal of groundwater from this environment (Fig. 4.1). It would seem, therefore, that the overburden had been supported by the considerably less dense material at its base, in a very delicate metastable equilibrium set up over long periods of time. Over about half of the area involved the bedrock surface was below the original groundwater-table. If it is accepted that the material filling or partly filling the fissures in bedrock, which projected above the groundwater-table, was also within reach of the water, then it follows that the metastable equilibrium was established in saturated overburden throughout the area (Fig. 4.2).

### 4.4 SUPPORT MECHANISM IN OVERBURDEN CHARACTERIZED BY INVERSE DENSITY

Practically all the previous investigations, from Donaldson (1963) to Kleywegt and Enslin (1973), have suggested mechanisms through which at least some, if not all, of the ground movements observed on the Far West Rand can be explained. However, insufficient attention has been paid to the apparently anomalous situation that derives from the least dense material lying deepest in the overburden, which is the inevitable result of the continual dissolution of the dolomitic bedrock. The ability of this latter material to support the more dense overburden, up to 100 metres or more thick (Fig. 4.2), is ascribed chiefly to arching and doming from the bedrock through bridges of chert fragments (and possibly dolomite floaters) and clay (the only cohesive constituent). In the

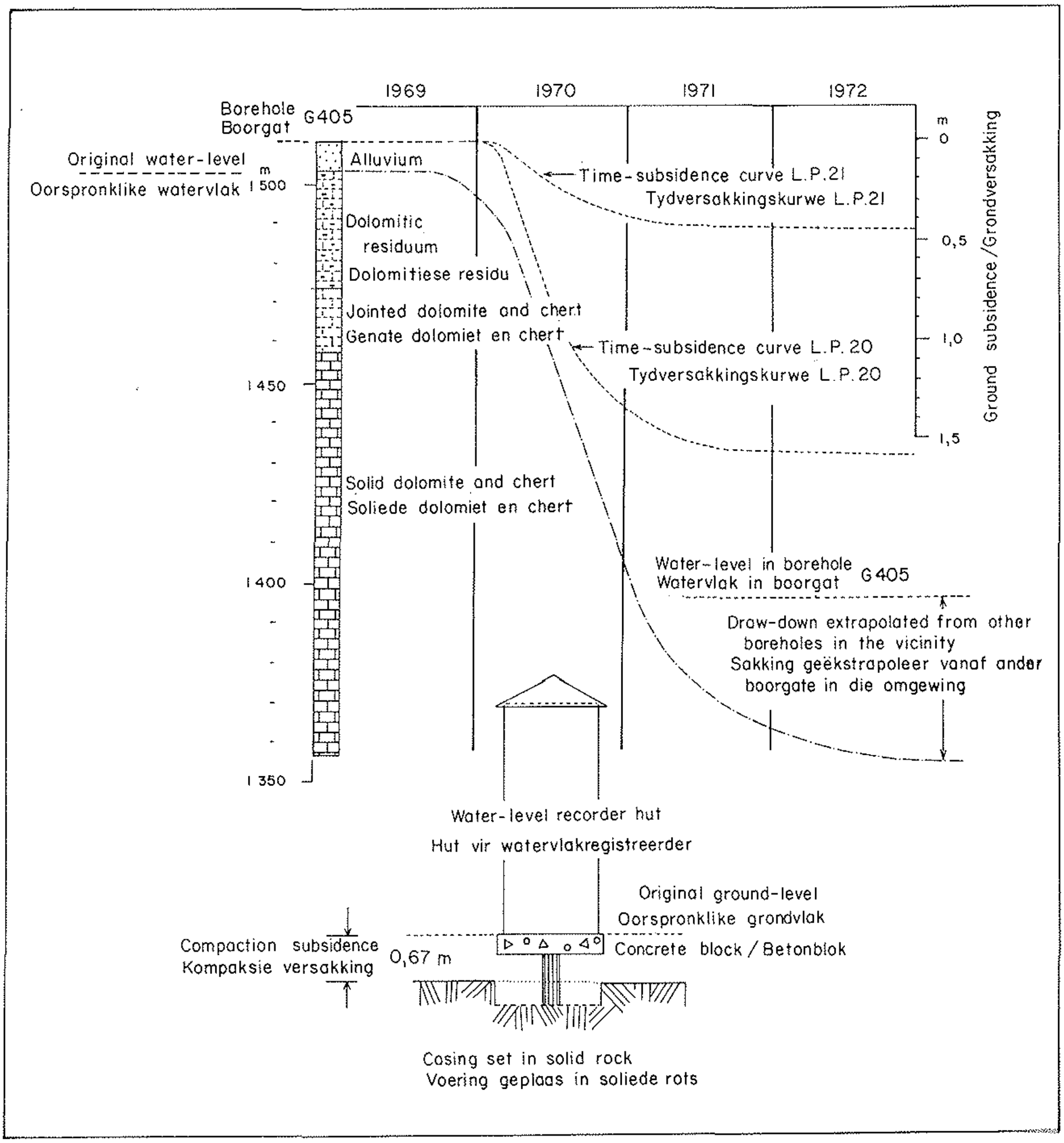



Fig. 4.1 – Water-level draw-down and ground subsidence at Borehole G405, Bank Compartment (after Kleywegt and Enslin 1973, Fig. 7. Published with permission of Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).

*Watervlaksakking en grondversakkings by Boorgat G405, Bankkompartement (volgens Kleywegt en Enslin 1973, Fig. 7. Gepubliseer met vergunning van die Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).*

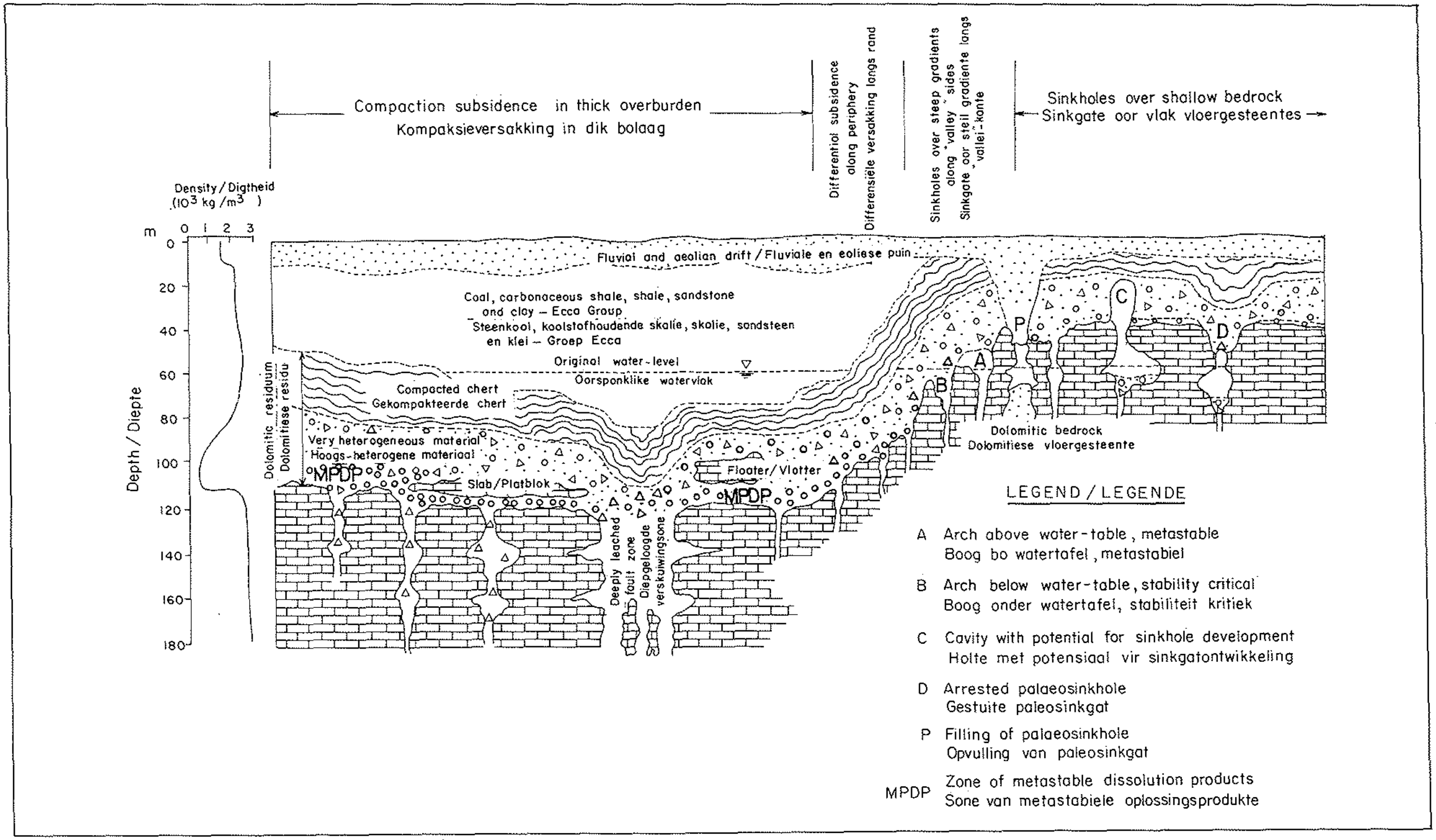
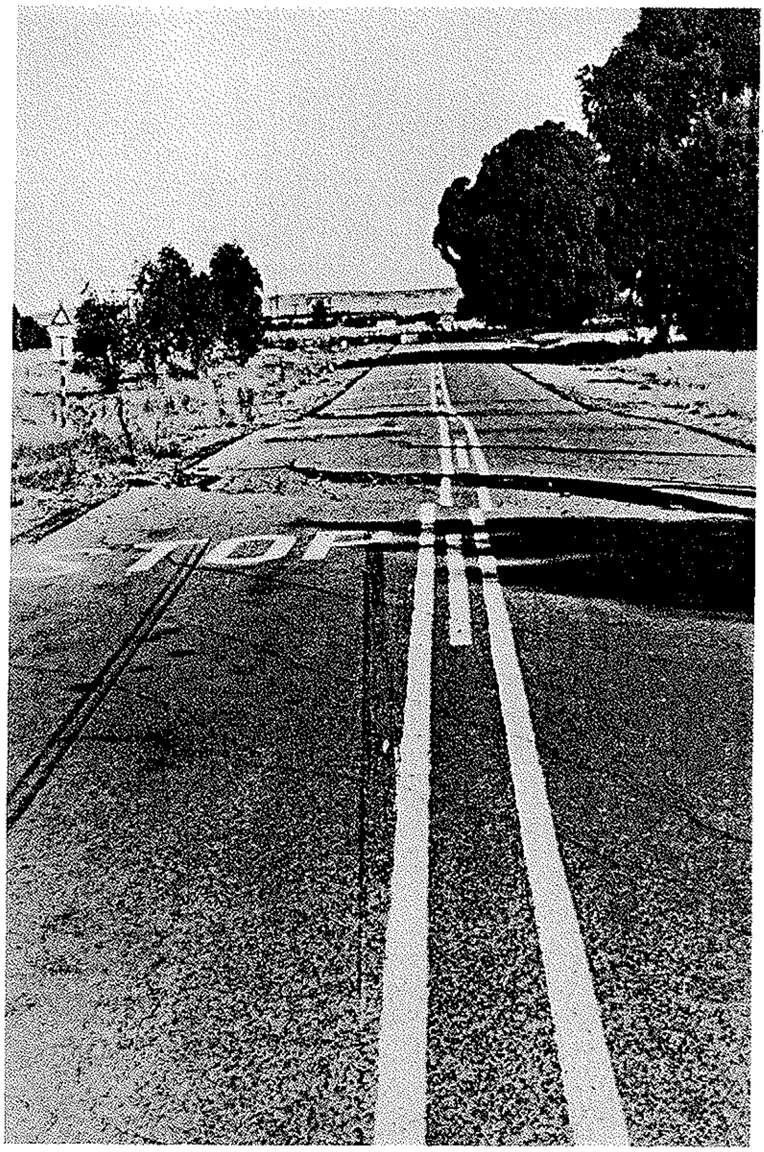



Fig. 4.2 – Semi-diagrammatic section through the Far West Rand dolomite and overburden, illustrating the relationship between environment and the type of subsidence or sinkhole (Geological Survey of South Africa).
*Halfdiagrammatiese snit deur die Verre Wes-Rand-dolomiet en -bolaag, wat die verhouding tussen omgewing en die tipe versakking of sinkgat, illustreer (Geologiese Opname van Suid-Afrika).*



Pl. 4.1 — Cracks in tarmac with vertical and lateral displacement of the road north of Bank Station due to differential subsidence (photo: Geological Survey of South Africa).
*Barste in teer met vertikale en sydlingse verplasing van die pad noord van Bankstasie weens differensiële sakking (foto: Geologiese Opname van Suid-Afrika).*

opinion of Roux (1977)* at least some of the support is provided by pore-water pressure.

### 4.5 CORRELATION BETWEEN TYPE OF GROUND MOVEMENT AND ENVIRONMENT

Difficulties have also been experienced when attempting to give general explanations for ground movements in the area as a whole. This is not so much because of the obvious heterogeneity of the overburden and the irregularities of the surface upon which it bears and, hence, the visualizing of actual bedrock prominences from which the arching develops, or the dimensions which allow the arches to remain stable; but because the type, magnitude and distribution of the ground movements tend to correlate more in a general way with their immediate environments than specifically. Thus it is possible for a very large-diameter sinkhole to form next to a series of relatively narrow chimneys, or for both ground subsidence and sinkholes to characterize a single locality.

### 4.6 CORRELATION BETWEEN TYPE OF GROUND MOVEMENT AND MECHANISM

It has been customary to ascribe ground subsidence to a compaction process and sinkhole formation to arch failure, in particular according to the mechanisms propounded by Terzaghi and Lobban respectively (Jennings 1966). The compactibility of the Karoo formations which are involved in subsidences - as opposed to sinkholes - is very small by comparison with that of the dolomitic residuum, however. For this and the foregoing reasons it seems preferable to ascribe both phenomena to related types of arch failure, and the differences in manifestation to broad differences in environment.

### 4.7 EFFECT OF DEWATERING ON OVERBURDEN STABILITY

According to Lobban (Jennings 1966) the stability characteristics of arches in a geological environment of this sort depend mainly on the cohesion and moisture condition of the constituent materials. With the progressive drop of the groundwater level in each of the dolomitic compartments concerned, however, the effective weight of the overburden increases and the weight increment is transferred to the supporting structures in the low-density residuum to the bedrock. The stability criteria are thereafter further affected as the materials dry out.

### 4.8 COLLAPSE AND COMPACTION IN DOLOMITIC RESIDUUM

The resultant ground movements should therefore be interpreted as being due to collapse or differential collapse and compaction of the dolomitic residuum, with the material characterized by inverse density making the greatest contribution to vertical shortening. The structures responsible for the pre-dewatering metastable state have been most effectively likened by Donaldson and Williams (1977)* to inverted egg trays or houses of playing cards through which the arching or doming can act. Their role during and/or after dewatering is seen as follows:

If the arches or domes are inadequate to support the spans of the increased weight, they collapse simultaneously or successively, having lost any possible support provided by pore-water pressure as well. Voids in the residuum as a whole tend to close and compaction of the whole column takes place. This is mainly true of thicker sections of overburden and, in particular, along wide "valleys" in the bedrock topography. At the ground surface the periphery of the subsidences may be characterized by slopes and/or well-developed and often wide cracks, depending on the ability of the overburden to accommodate the differential movement (Pl. 4.1 and Figs 3.3, 3,4 and 4.2).

Where the overburden is less thick, the weight increment correspondingly smaller and the structures such that stability is maintained even after drying out, compaction of the residuum above and around the arches or domes takes place as pore water drains. This leads to smaller scale differential subsidence at the ground surface than described (see 4.8, second paragraph).

If the stability attained (as described in the third paragraph of 4.8) is over a fissure or void capable of accepting significant quantities of disaggregated overburden, some extraneous disturbing agency can cause the arch or dome to migrate towards the ground surface and, after the collapse of a thin remaining roof, leave an open chimney or sinkhole (Fig. 4.2). Typical extraneous agencies of the sort are storm or waste water infiltrating along cracks or into the overburden in abnormal quantities, and strong earth tremors originating in mining activity (Kleywegt and Enslin 1973). Very large sinkholes are considered to develop as the result of the coalescing of several closely spaced structures.

## 5. GROUND SUBSIDENCE AND SINKHOLES

### 5.1 EFFECT ON THE INHABITANTS OF THE AREA

Although ground subsidence has damaged properties, buildings, roads and mine installations, etc. in the past the associated psychological effect on the public has been mild by comparison with that which followed the accelerated occurrence of the sinkholes. This factor in the early 1960s threatened to harm the mining activities because of the nervous and uncertain state in which it left the inhabitants of the area. It was only by a concerted effort on the part of the State and the mining authorities that irreparable harm was not done during the few initial, difficult years when many sinkholes occurred concurrently with ground subsidence.

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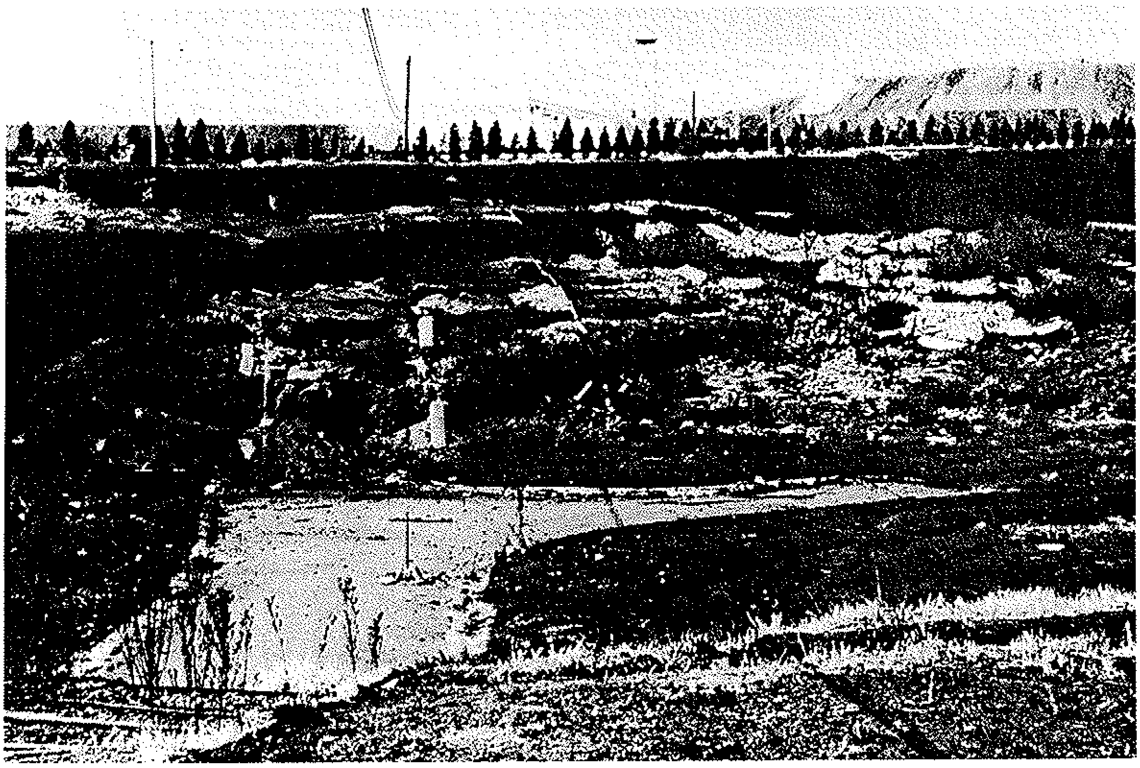
*P. Roux, Geol. Surv. S. Afr., pers. commun.

*G.W. Donaldson and A.A.B. Williams, C.S.I.R., pers. commun.



Pl. 5.1 – Slow surface subsidence, Schutte's Depression, Carletonville (with acknowledgement to IAHS Publication 89, Pl. 2).

*Stadige oppervlaksakking, Schutte se Depressie, Carletonville (met erkenning aan IAHS-publikasie 89, Pl. 2).*

## 5.2 ACTION TAKEN TO RESTORE CONFIDENCE IN THE AREA

The State contributed by addressing several public meetings in the area, by delineating areas suitable for development, by completing several public buildings or additions to them, particularly schools, in providing an information service to inhabitants once a week and by the regular inspection of properties by the State Technical Co-ordinating Committee.

In addition this committee held monthly meetings to advise the public on the safety of properties and to review the progress and guide the intensive geological and geophysical work being carried out. At the same time the Chamber of Mines sponsored an intensive research programme into the possibility of locating underground voids, and the Far West Rand Dolomitic Water Association, through dealing with claims for compensation of damages attributable to dewatering, assisted in no mean manner. The various mine managements concentrated particularly on the installation of warning devices in the form of surface and underground bench-marks in addition to effecting geological and geophysical investigations on their properties.

The State Technical Committee had a very difficult task to perform at that time. It was committed to giving advice on the safety of properties while it had, in general, a limited amount of information available and practically no experience of similar conditions on which to base its deliberations. However, the committee realized that it was impossible to locate directly the voids or similar conditions which could lead to sinkhole formation and a technique of evaluation based on the integration of geological and geophysical data was therefore developed for the assessment of potential danger. The various parameters that require consideration are:

1. Bedrock configuration relative to the level of the original water-table.

2. Nature and thickness of the overburden.

3. Nature and amount of ground movement and if possible depth(s) at which movement (compaction) is likely to take place.

The mean bedrock configuration relative to the level of the original water-table is determined from residual gravity maps which are compiled in such a way that zero residual gravity, excluding the effects of narrow structures or steep lateral changes in bedrock configuration, indicates the mean bedrock surface to be at or near to the level of the original water-table and, for positive and negative residual gravity values, above and below this level respectively. At a first approximation, therefore, it can be assumed that areas of negative residual gravity are areas of potential subsidence, the extent depending on the nature of the material being dewatered. Better approximations of the area that may be affected have been obtained by adopting Skeels' (1963) method of interpretation, using mainly the horizontal physical dimensions of the causative body rather than the possible absolute depth, or by gravity modelling techniques, particularly 2-D modelling. Kleywegt and Enslin (1973) and Enslin et al. (1976) have given more detailed explanations. It must be emphasized that without the extensive gravity surveys, carried out on a 100-m spacing in open areas and 20- to 30-m spacing in towns over a total area of several hundred square kilometres, the committee would not have been able to function effectively.

Electrical resistivity surveys were tried but are obviously unsuitable in the towns, and elsewhere the results were severely affected by the highly conductive outliers of Karoo rocks. Due to the density inversion at the bedrock surface, seismic refraction surveys were also unsuccessful.

The nature and thickness of the overburden materials, particularly the Karoo rocks, and the depth and thickness of low bearing capacity, leached dolomitic materials were and still are determined by drilling percussion holes and examining the samples retrieved.

The nature and amount of ground movement is determined by regular relevelling of surface bench-marks and by regular measurement of telescopic bench-marks.

From these parameters the committee had to assess the possibility or cause of ground movement and determine whether large voids or cavernous conditions which might collapse were present. Quite often potentially weak zones were deduced but they could not be located by subsequent drilling and in such cases a conservative approach was adopted. Many stands have been declared unsuitable for development and many houses have been evacuated and demolished.

## 5.3 EXTENT OF GROUND SUBSIDENCE

In gravity-low areas where the dolomitic bedrock is as much as 100 m below the original water-level, the ground subsidence has varied from zero, where Karoo shale and sandstone rest directly upon the bedrock, to 8 m in the case of the so-called Schutte's Depression in Carletonville where there is a large thickness of compactible material between the Karoo rocks and the dolomitic bedrock (Pl. 5.1). In most cases the subsidence has been less than 1,5 m (Kleywegt and Enslin 1973).

Over deeply leached zones the maximum ground settlement is usually in the central portions, whereas the greatest differential movement takes place over the edges (Figs 3.3, 3.4 and 4,2). Houses have settled as individual units by as much as 4 m with only minor damage in the central portions of the subsidences while those over the edges were severely damaged by differential movement to the extent that they collapsed or demolition was recommended (Kleywegt and Enslin 1973).

## 5.4 GROUND SUBSIDENCE AS A FUNCTION OF TIME

Over the deeply leached areas the ground subsidence usually commences shortly after dewatering of the highly compactible materials has begun. The rate of subsidence depends on the nature of the overburden being dewatered and on the rate of water-level draw-down. Depending on these factors the subsidence may commence one to twelve months after the onset of dewatering.

A typical ground subsidence curve (Fig. 4.1) reproduced from Kleywegt and Enslin (1973) reveals an accelerating rate of subsidence initially, then a maximum rate which was maintained for a period, after which it decreased gradually to zero. Thereafter minor adjustments took place sporadically, apparently in response to the reduction of friction between rigid and subsiding blocks as a result of strong earth tremors from the nearby mines or the excessive infiltration of water during thunderstorms. These movements are usually within the observational accuracy and cannot be located immediately by relevelling but only as their cumulative effect becomes evident over long periods of time. The ground response described is that due to the dewatering of a single zone of leaching above the dolomitic bedrock in the area about Borehole G405. At that locality (Fig. 4.1) most or all the compaction must have occurred above the bedrock since the total ground subsidence, as interpolated from levelling points L.P. 20 and 21 close to the borehole, experienced the same amount of negative movement as the apparent positive movement of the casing relative to the ground surface, viz. 0,67 m. It has been found that final stability is usually attained 6 to 24 months after the water-level has passed through the particular compactible horizon. Figure 3.1 shows the gravity-low areas, in that part of the Oberholzer Compartment which were surveyed, in which ground subsidences could occur depending on the compactibility of the material and the extent of the dewatering.

In several instances the stability which was setting in, or had set in, was upset by a renewed cycle of ground movement in response to the dewatering of a deeper compactible horizon. This has been proved by drilling holes through the dolomitic "bedrock" to a second zone of leaching, exceeding the depth of the first by as much as 100 m or more, and by regular levelling of bench-marks consisting of telescopic borehole casings which were originally installed in the early 1960s at various depths in the borehole. In such cases the surveys indicated that the ground surface and the telescopic borehole casings, fixed in the overburden and the dolomitic "bedrock", were subsiding at the same rate. The dolomite, into which the casings were cemented, appears to be slabs which are detached from the main mass of bedrock and rest on a deeper horizon of wad and leached material which compacted when it was dewatered. This caused the slabs and the overlying overburden to settle as a unit after the initial ground subsidence due to dewatering of the upper zone of leaching had taken place.

The area about Borehole G610, described by Kleywegt and Enslin (1973), is such an example. The ground surface there has subsided by about 2 m while the apparent positive movement, relative to the ground, of the telescopic casing cemented in "bedrock" at a depth of 150 m, was only about 0,15 m.

## 5.5 GROUND SUBSIDENCE IN THE BANK-STATION AREA

Figure 5.1 gives the residual gravity map of the area around the village of Bank while Figure 5.2 shows the interpreted areas of potential subsidence, as well as contours of actual subsidence at December 1972, two-and-a-half years after dewatering had commenced (Kleywegt and Enslin 1973). The mine managements determined ground subsidence by regular relevelling of the original gravity observation points, which were on a 30-m grid. Figure 5.3 is a profile through this area and shows the ground subsidence relative to the residual gravity, the geology and the water-table. The material in the central part of this wide zone is obviously not compactible locally and there is in fact an indication, from the boreholes and the residual gravity, that the dolomitic bedrock is somewhat shallower and that the overburden is somewhat more dense than in the adjacent areas of subsidence.

## 5.6 EVALUATION OF THE POTENTIAL DANGER OF SINKHOLE FORMATION

As it was found to be just about impossible to locate individual underground voids which could lead to the forming of sinkholes, a qualitative method of evaluating the potential danger was evolved as described in 5.2. It was found that most sinkholes occurred in the area where the original water-table was less than about 30 m from the ground surface. Because of the low gradient of the groundwater-table this is effectively the low-lying area along the Wonderfontein Spruit. In these areas the occurrences of sinkholes could be related to specific zones which could mostly be delineated geophysically.

Figure 5.4 taken from Kleywegt and Enslin (1973) depicts the numerical distribution of sinkholes, and also the percentage area affected by them in the Bank Compartment, against the depth of the original water-level about two-and-a-half years after the dewatering had commenced. In the eastern part of the Venterspost Compartment along the Wonderfontein Spruit, Kleywegt and Enslin (1973) showed that sinkholes occurred on gravity highs, on gravity gradients or over relatively narrow gravity low zones (Fig. 5.5). In each case bridging of voids or cavernous conditions in near-surface dolomitic bedrock could be invoked with the final trigger as set out in the fourth paragraph of 4.8. Over the larger areas of low gravity, however, large-scale subsidence has occurred through the simultaneous collapse of the

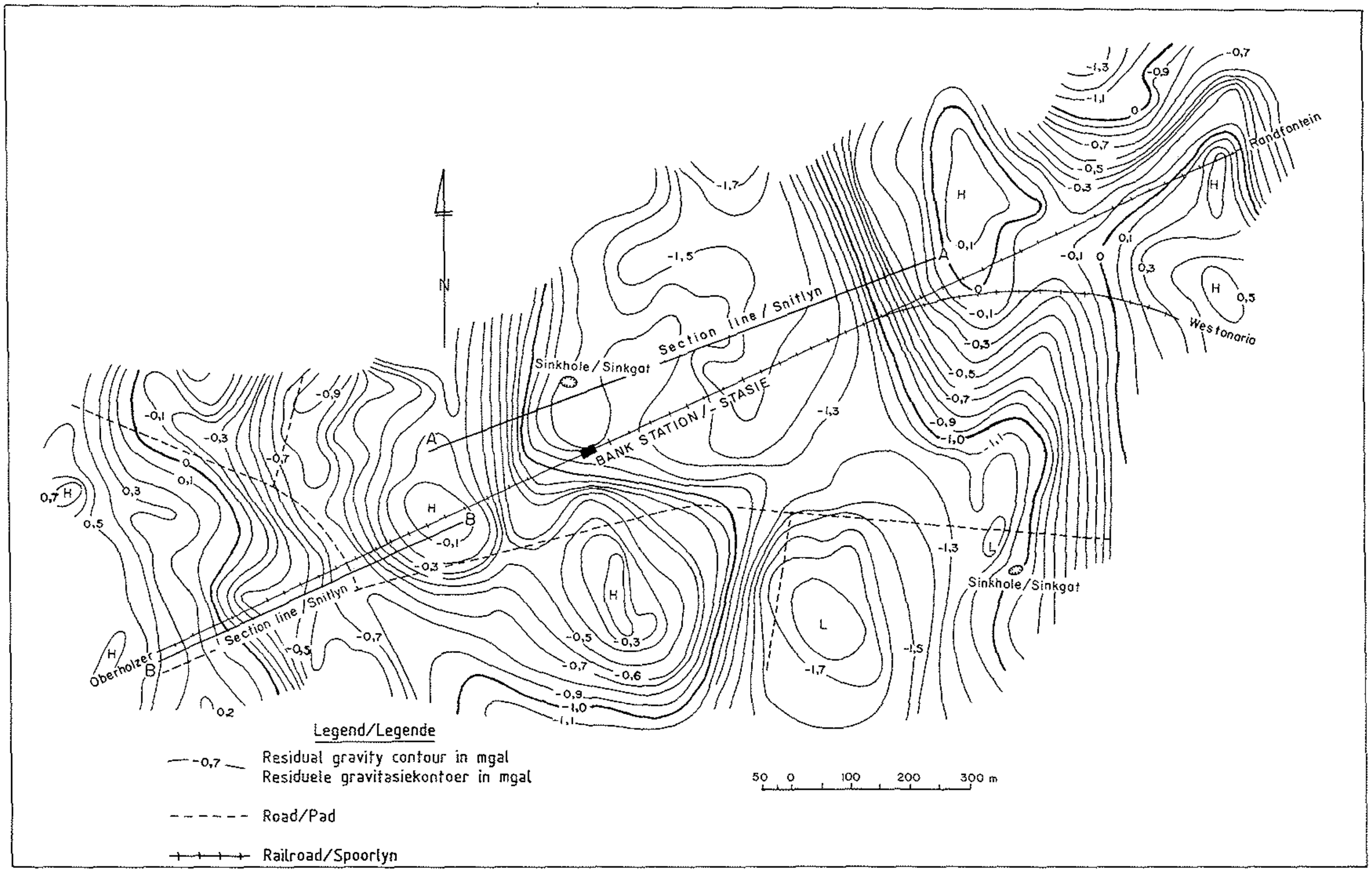



Fig. 5.1 — Residual gravity map of Bank and its immediate environs (after Kleywegt and Enslin 1973, Fig. 2. Published with the permission of Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).
*Residuele gravitasiekaart van Bank en die onmiddellike omgewing (volgens Kleywegt en Enslin 1973, Fig. 2. Gepubliseer met vergunning van die Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).*

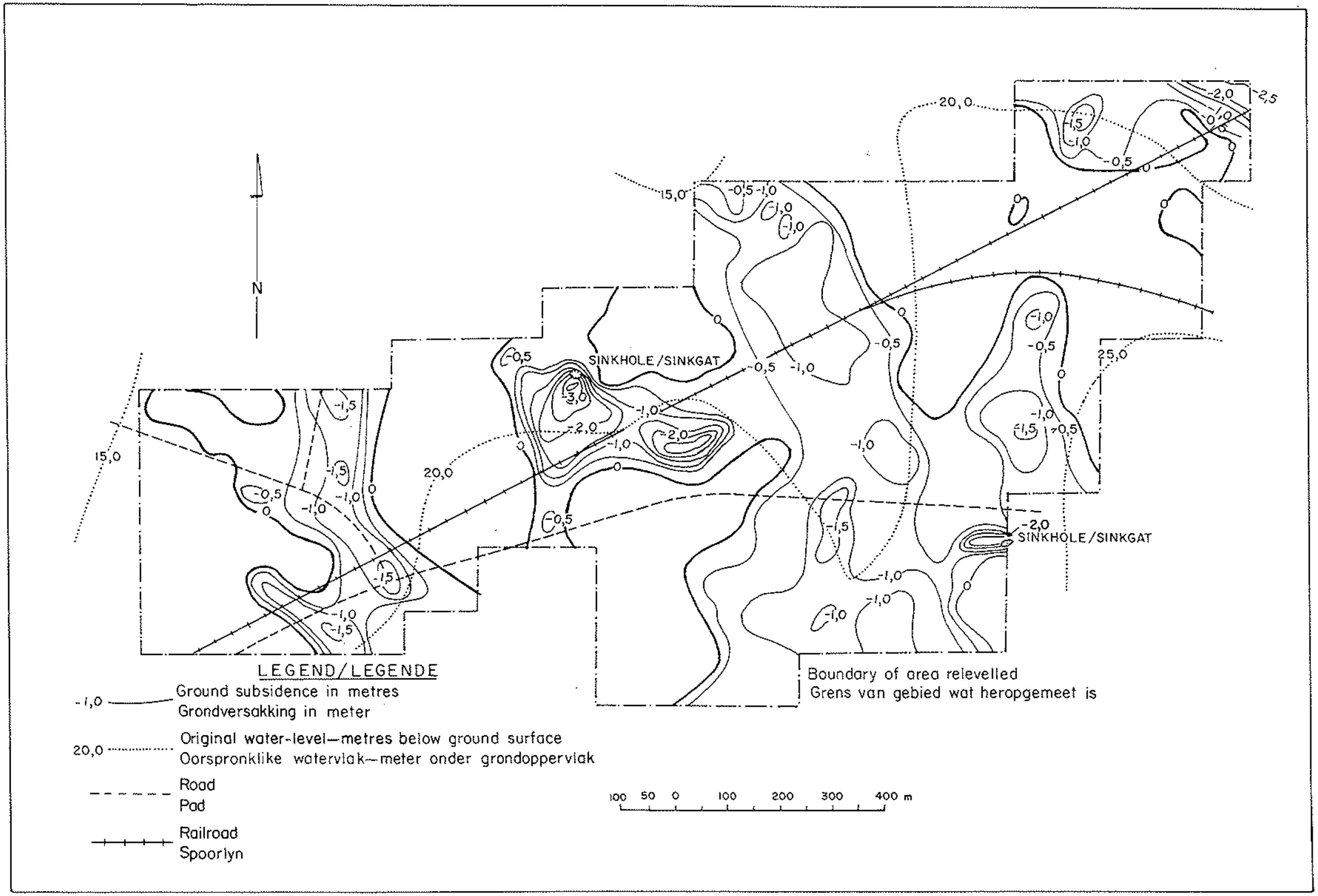



Fig. 5.2 — Ground subsidence at Bank and its immediate environs in December 1972, about 2,5 years after dewatering commenced (after Kleywegt and Enslin 1973, Fig. 6. Published with the permission of Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).
*Grondversakking by Bank en die onmiddellike omgewing in Desember 1972, ongeveer 2,5 jaar nadat ontwatering begin het (volgens Kleywegt 1973, Fig. 6. Gepubliseer met vergunning van die Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.)*

Grondversakking by Bank en die onmiddellike omgewing in Desember 1972, ongeveer 2,5 jaar nadat ontwatering begin het (volgens
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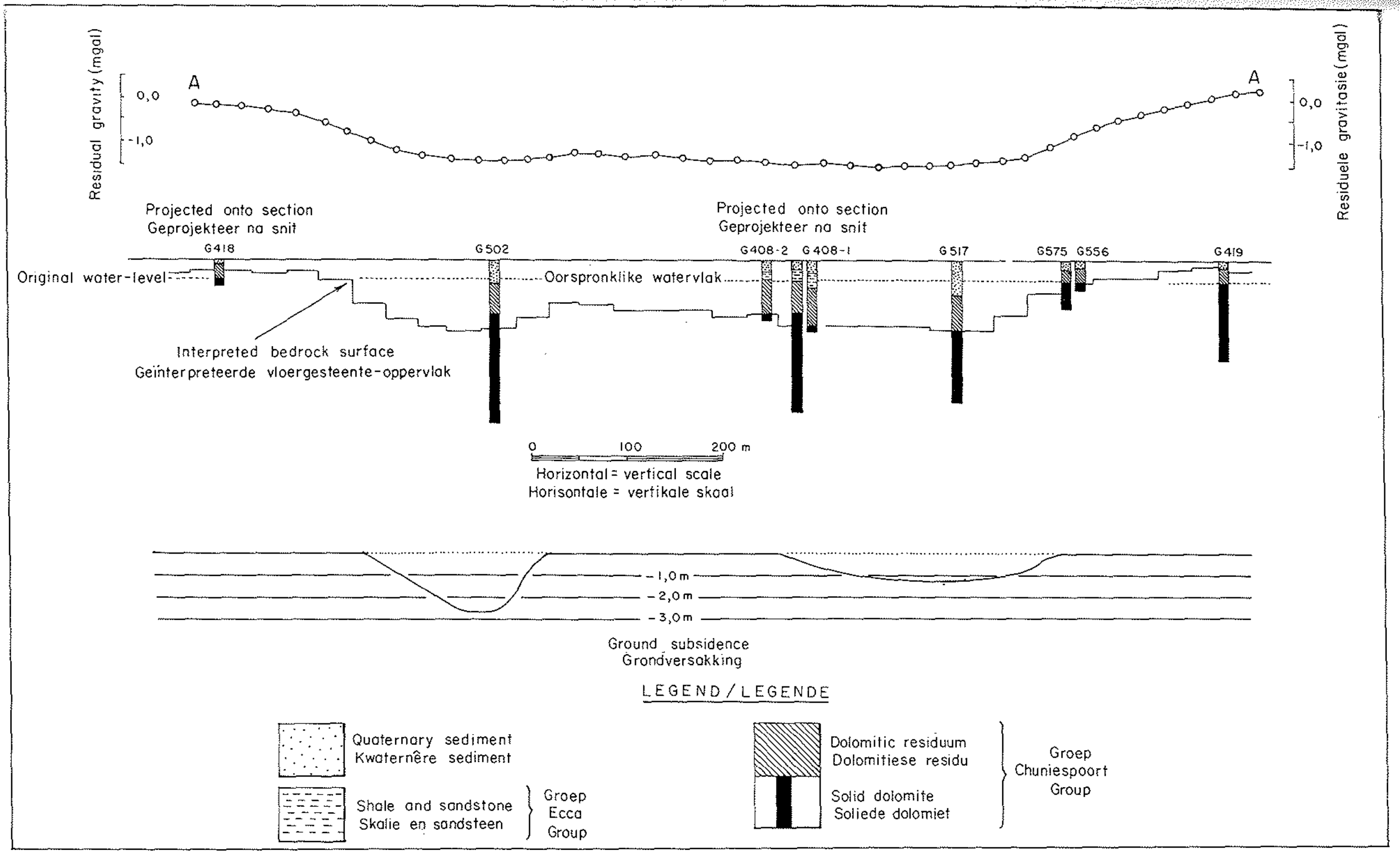



Fig. 5.3 — Residual gravity, borehole geology, interpreted geology and ground subsidence profile A—A north of Bank Station in the Bank Compartment. See Figure 5.1 (after Kleywegt and Enslin 1973, Fig. 4. Published with the permission of Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).

*Residuele gravitasie, boorgatgeologie, geïnterpreteerde geologie en grondversakkingsprofiel A—A noord van Bankstasie in die Bankkompartement. Kyk Figuur 5.1 (volgens Kleywegt en Enslin 1973, Fig. 4. Gepubliseer met vergunning van die Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).*

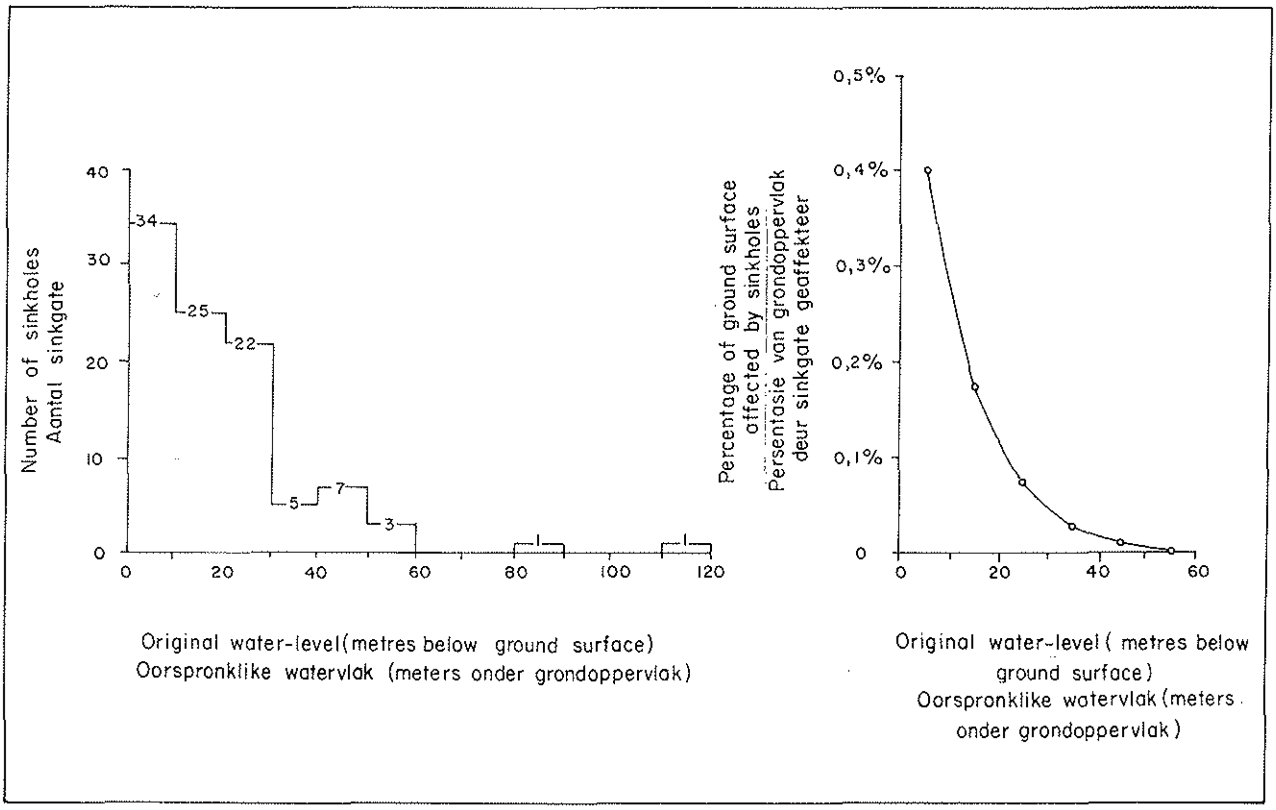



Fig. 5.4 — Sinkholes in the western half of the Bank Compartment in December 1972, about 2,5 years after dewatering commenced (after Kleywegt and Enslin 1973, Fig. 8. Published with the permission of Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).
*Sinkgate in die westelike helfte van Bankkompartement in Desember 1972, ongeveer 2,5 jaar nadat ontwatering begin het (volgens Kleywegt en Enslin 1973, Fig. 8. Gepubliseer met vergunning van die Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).*

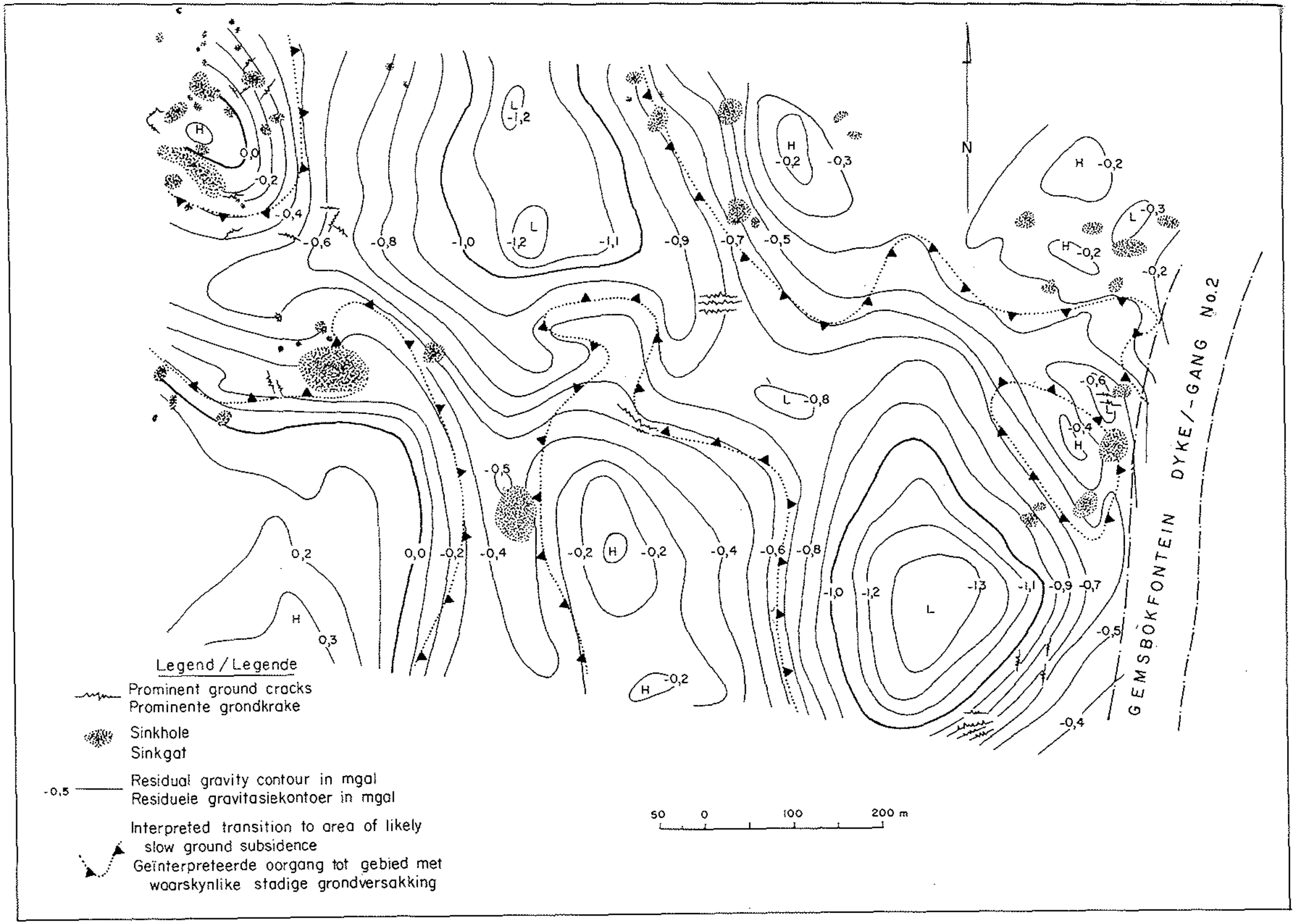



Fig. 5.5 — Sinkholes along the Wonderfontein Valley at the eastern end of the Venterspost Compartment (after Kleywegt and Enslin 1973, Fig. 3. Published with the permission of Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).
*Sinkgate langs die Wonderfonteinvallei teen die oostelike grens van die Venterspostkompartement (volgens Kleywegt en Enslin 1973, Fig. 3. Gepubliseer met vergunning van die Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).*

arches and domes spanning voids and cavernous conditions as explained in the second paragraph of 4.8, and sinkholes have not been able to develop. The only sinkholes which have formed in such areas occur over the transition zone to the gravity high and are probably related to subsurface irregularities of the dolomitic bedrock at shallower depths.

The high incidence of sinkholes in these low-lying areas is thus seen to be the result of collapse into voids of bridges at shallow depths under the disequilibrium introduced by the dewatering of these materials, and, if not triggered thereby, then by extraneous circumstances such as infiltrating water and/or severe mine temors. Due to the shallowness of the original water-table the percentage area which could be potentially affected is large. This decreases significantly over the higher ground away from the Wonderfontein Spruit, however, because much more of the smaller scale fissuring on gravity-high areas tends to develop above the original water-level and the greater thickness of overburden can absorb or bear the collapsed arches which might result from the dewatering. Over higher lying areas the conditions for the formation of sinkholes are thus less favourable.

Near the top of the Chuniespoort Group where the percentage of subhorizontal intercalated layers of insoluble chert increases, large gravity-low features have, however, not been entirely free of sinkholes. In most instances the contribution of large volumes of infiltrating water could be demonstrated. Infiltration took place through ground-subsidence cracks in the Twyfelvlakte water course, over ground on which water was spread out south-west of Carletonville to recharge the compartment (Enslin et al. 1976) or through leaking or broken water pipes as at Blyvooruitzicht sinkhole (Pl. 5.2) which engulfed 2 houses and parts of two others and resulted in the loss of 5 lives (Bezuidenhout and Enslin 1969). Kleywegt and Enslin (1973) claim that deeply leached zones in the dolomite reflected by the gravity lows are in effect equivalent to large-scale, relatively narrow structures and that the weakening which has resulted from the progressive dewatering has been aided by the shaking of the ground by strong mine tremors and by infiltrating water. As a result one of the deeper arches forming a bottle-neck in the cavernous structure collapses and triggers the collapse of successively higher cavernous zones. The resultant sinkholes are generally, though not always, larger than those of the low-lying areas and have surface dimensions of 20 to 100 m and are 15 to 50 m deep.

In the area between the Wonderfontein Spruit and the higher ground, fewer sinkholes have occurred because the weakening of narrow structures at depth has been countered by the thick overburden, often consisting of outliers of Karoo sediments. This intervening area constitutes a large part of the dolomitic ground in the dewatered compartments and comprises the ground where the depth of the natural water-table varied between 30 m and 80 m.

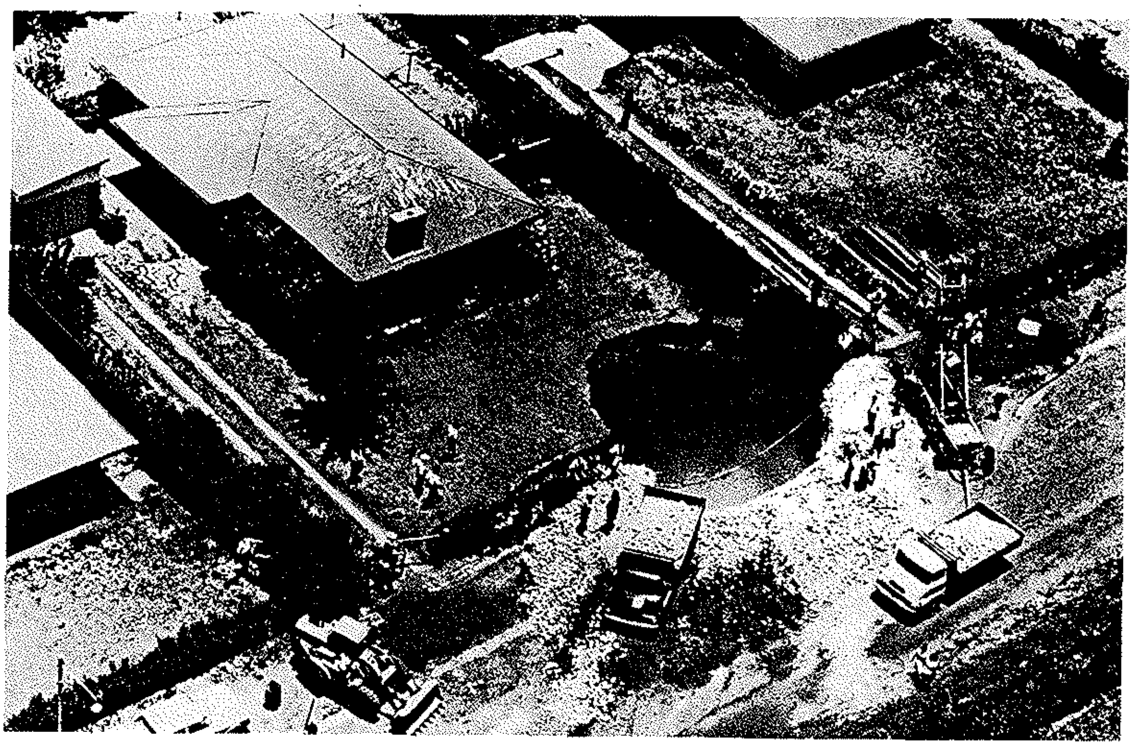
## 5.7 PALAEOSINKHOLES

After relative stability had set in, rejuvenation in parts or the whole of Quaternary palaeosinkholes, filled with red aeolian sand and waterborne gravel, sand and clay, was observed and described by Kleywegt and Enslin (1973). The reactivation is ascribed partly to the hour-glass mechanism suggested by Donaldson (1963) following the ingress of storm or other excess water from the surface and consequent piping of the filling at depth (Fig. 4.2). In the Ventersspost Compartment there is also a clear correlation between the rejuvenation of palaeosinkholes and the temporary return of water from minus 100 m to minus 60 m relative to the original water-level, indicating a definite sensitivity of the metastable filling to a single cycle of drying and rewetting.

Palaeosinkholes have been located by reinvestigating the small gravity anomalies associated with them (less than -0,15 mgal) or by exploring occurrences of increased thicknesses of Quaternary overburden that have been found during the normal investigation phase. These areas often lie slightly lower than the immediate environs and tend to accumulate surface water or water from roofs. Saturation of the soil assists its collapse as the subsurface structure is again weakened (Pl. 5.3).

In one township 16 such palaeosinkholes have been located and instructions were given that the properties be evacuated. Of these, three have collapsed and in another town a sinkhole occurred only two months after part of a school playground had been declared unsuitable following an intensive investigation. Figure 5.6, taken from Kleywegt and Enslin (1973), shows one such example of a sinkhole which was finally triggered in Westonaria after water from roofs of adjacent houses had collected and infiltrated the palaeosinkhole. As the sinkhole occurred six hours after a particularly severe tremor in the gold mine underlying part of the township, it is felt that the tremor also contributed to the collapse.

Pl. 5.2 — Sinkhole at Blyvooruitzicht (with acknowledgement to IAHS Publication 89, Pl. 2).
*Sinkgat by Blyvooruitzicht (met erkenning aan IAHS-publikasie 89, Pl. 2).*



Pl. 5.3 — Rejuvenated palaeosinkhole, Kaolin Street, Carletonville (with acknowledgement to IAHS Publication 89, Pl. 4).
*Verjongde paleosinkgat, Kaolinstraat, Carletonville (met erkenning aan IAHS-publikasie 89, Pl. 4).*

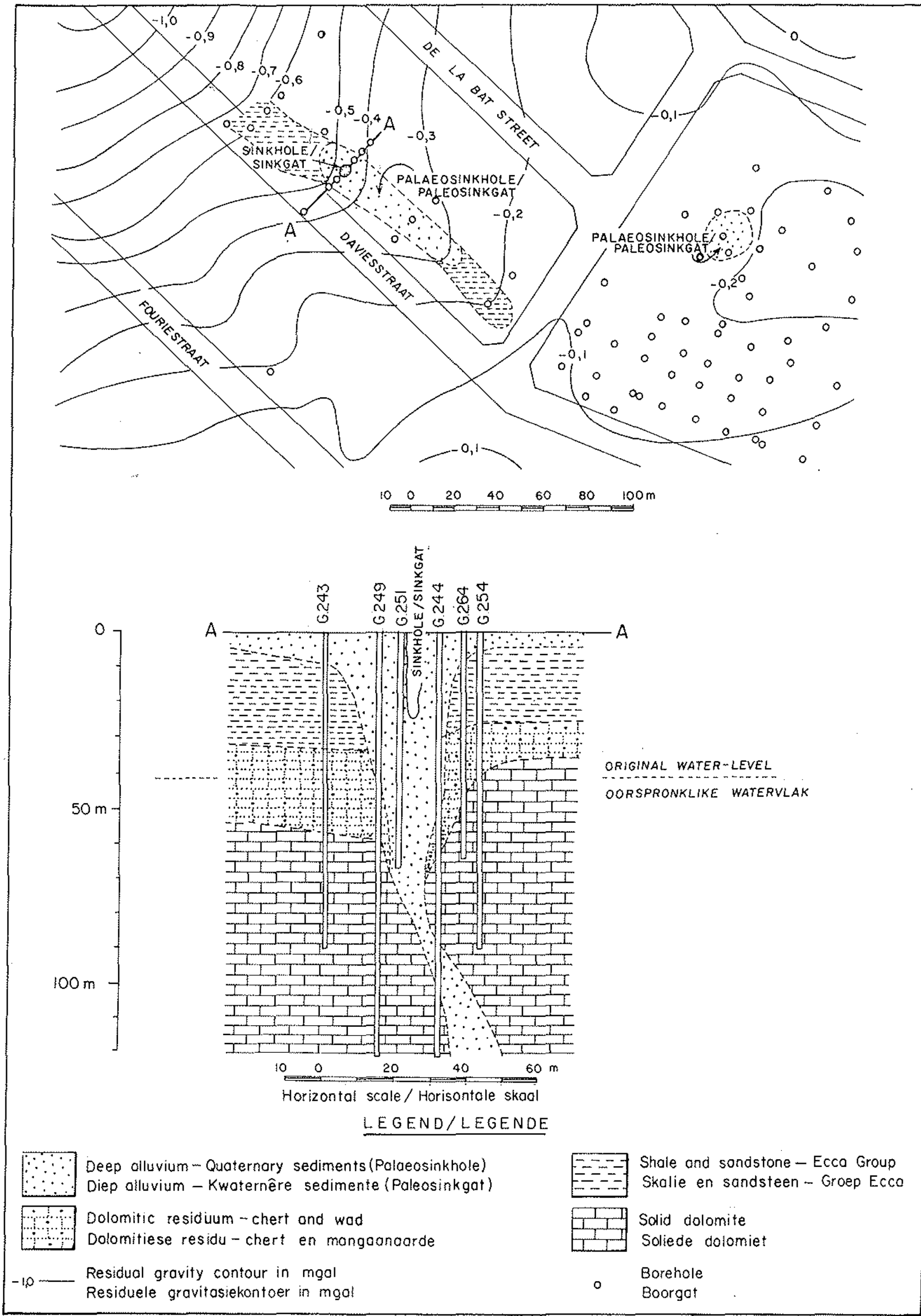



Fig. 5.6 — Sinkhole and palaeosinkhole conditions at the western end of Davies Street, Westonaria (after Kleywegt and Enslin 1973, Fig. 10. Published with the permission of Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).
*Sinkgat- en paleosinkgattoestande by die westelike end van Daviesstraat, Westonaria (volgens Kleywegt en Enslin 1973, Fig. 10. Gepubliseer met vergunning van die Deutsche Gesellschaft für Erd- und Grundbau, Essen, F.R.D.).*

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