underground 100 m deep, and the phenomenon of land-surface sinking is apparent in the adjoining parts centering around the well. Accordingly, it is clear from experiments and the conditions of the area that consolidation subsidence can occur by the lowering of underground water pressure due to pumping from the base of thick alluvial formation, even if there is water on the surface.

SURFACE SUBSIDENCE AND SINKHOLES IN THE DOLOMITIC AREAS OF THE FAR WEST RAND, TRANSVAAL, REPUBLIC OF SOUTH AFRICA

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ABSTRACT

The gold-bearing reefs of the Far West Rand, from where nearly one-fifth of the published world annual production for 1967 was derived, underlie 1200 metres of dolomite—the most important aquifer of the Republic.

The dolomitic ground water, which is stored by nature in separate dyke bounded compartments (a typical one covers 160 square kilometres and has a storage capacity of 700,000 megalitres) is apt to flow into the mine workings at enormous rates, depending on the number of post-dolomite faults cutting the workings and the hydrological characteristics of those faults.

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As a general policy the dolomitic ground-water compartments are dewatered by pumping and the disposal of the pumped water in such a way that it cannot return to the particular compartment and recirculate through the mines. A saving of approximately R 100 million in pumping costs will be effected and the safety of mining is increased by preventing recirculation.

Dewatering, however, results in differential subsidence of large areas and the formation of sinkholes; certain areas have thus become unsafe for occupation. Damage to buildings caused by subsidence, and the cost of replacements, research and work to improve safety has amounted to more than R 25 million.

The geological and hydrological factors causing subsidence and sinkholes are discussed. A gravity method of delineating areas of potential subsidence and zones where the conditions are favourable for the formation of sinkholes is described.

RESUME

Le reef aurifère du l'Extrême Rand-Occidental, d'où presque la cinquième partie de la production mondiale d'or, publiée pour l'année 1967 provient, se trouve au-dessous d'une couche de 1 200 mètres d'épaisseur de dolomite. Cette couche constitue en même temps l'aquifère le plus important de la République.

L'eau souterraine de la dolomite se trouve de façon naturelle, accumulée en compartiments limités par des dykes. Un de ces compartiments, typique pour l'ensemble, couvre 150 000 km² et possède une capacité d'accumulation de 150 000 millions de gallons impériaux. L'eau souterraine est portée à s'écoaler dans les travaux miniers en quantités énormes, dépendant du nombre des failles postdolamitiques, coupées par les travaux miniers et les caractéristiques hydrogéologiques des failles.

Le mode d'action général est de drainer les compartiments d'eau souterraine par des machines d'épuisement. L'eau pompée est disposée de façon à rendre impossible la réoccupation d'un compartiment drainé et la recirculation à travers la mine. En empêchant la recirculation il est possible d'économiser environ 100 millions Rands en dépense de travaux d'épuisement et en même temps d'agrandir la sécurité dans la mine.

Le drainage des mines a eu cependant comme résultat une subsidence différentielle des régions étendues et la formation de dolines. Certaines régions sont ainsi devenues dangereuses pour l'occupation. Le dommage causé par la subsidence des bâtiments, les dépenses de leur replacement, les dépenses des recherches et celles des travaux d'amélioration de la sûreté, s'élèvent à plus de 25 millions Rands.

Les facteurs géologiques et hydrogéologiques qui causent la subsidence et la formation des dolines sont discutés. Une méthode de gravimétrie qui sert à tracer les régions de subsidence potentielle et les zones favorables à la formation des dolines est décrite.

When the gold mines on the Far West Rand came into production after the Second World War, it became apparent that much more water was being made here than in any of the other fields in the Witwatersrand Basin.

The cost of pumping water from the mines became an important factor in the economics of the field and the possibility of large inrushes of water into the workings presented itself as a major mining hazard.

The gold field of the Far West Rand (figs. 1 and 2) in the Transvaal covers some 750 sq. km and lies in a comparatively narrow block measuring 50 km along the strike and 15 km along the dip of the reefs. This area has become one of the most important gold-producing fields in the world. During 1967 the gold produced by the nine working mines (a tenth mine was then in the shaft sinking stage) amounted to 7,610,000 ounces or 18.8 per cent of the published world production figure of 40,500,000 ounces. The total gold produced in the Republic of South Africa that year was 30,532,880 ounces, of which 23.45 per cent was mined in this comparatively small field.

The total amount of gold produced in this field up to the end of 1968 was 80,062,566 ounces, which at the present price of of R25¹ an ounce has a value of approximately R2 billion. It is estimated that the amount of gold in the still unmined auriferous beds is approximately 240 million ounces, worth nearly R6 billion at the present price.

The gold remaining in this field is of significant economic importance and every effort will be made to mine as much of it as is economically practicable. It is, therefore, impera-

1. R1 = approximately US $1.4.
tive that the hazards of inrushes of water into the workings be countered and that pumping costs be held to a minimum.

As recently as October, 1968, an unprecedented inrush of water estimated at 365 megalitre\(^1\) per day broke through into the workings of the West Driefontein Gold Mine when settling of the roof of a stope took place. Only by the quick action and ingenuity on the part of the responsible mining engineers was the mine saved from being completely flooded, and it is a tribute to their skill and organisation that the entire labour force was successfully evacuated from underground without a single casualty.

**FIGURE 1.**

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**THE GEOLOGICAL SETTING**

In the Far West Rand the auriferous reefs of the Witwatersrand System and the Ventersdorp Contact Reef which are mined, underlie the Dolomite Series of the Transvaal System. The latter system is subdivided in descending order as follows:

- Pretoria Series
  - shale, quartzite, lava and intrusive diabase.
- Dolomite Series
  - dolomitic limestone and chert.
- Black Reef Series
  - quartzite and subordinate shale.

The Dolomite Series, which has a general dip of 6° to 12° to the south is about 1,200 metres thick in this area (fig. 3) and underlies the fairly flat Wonderfontein Valley which is eight to fifteen kilometres wide. Chert occurring in thin layers, mainly in the upper

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1. One megalitre = 264,178 US gallons;  
   = 219,980 British gallons.
150 metres of the Series, and the lower quartzites of the Pretoria Series form the hills which are the southern boundary of the Valley, and rise 100 to 200 metres above the river bed. The Black Reef Series and rocks belonging to the Witwatersrand System and the Older Granite outcrop in the low hills to the north of the Valley. Sandstone, shale and tillite of the younger Karoo System form a number of outliers on the Dolomite Series.

The soil cover of the Dolomite consists of \textit{in situ} weathered dolomite and chert, wad and transported aeolian sands of Pleistocene age.

Of the constituents of the dolomite, the carbonates of lime and magnesium dissolve slowly in dilute acidic ground-water percolating along fault planes and fissures and are removed in solution; the insoluble oxides of iron and manganese, as well as the weathered chert, remain more or less \textit{in situ} to form a light honeycombed residue. The manganese-rich material, called wad, compacts on being dewatered and such compaction may give rise to subsidence of the surface.

\textbf{GEOHYDROLOGY}

The Dolomite Series, which covers about 14,000 sq. kilometres in the Transvaal, forms the most important aquifer in the Republic. It is divided into a number of separate ground-water compartments by watertight syenite or diabese dykes (figs. 2 and 3). On the Far West Rand these dykes, which intruded the sediments along tension faults, generally strike in an approximate north-south direction at right angles to the strike of the formation. In each of the compartments the ground water is contained in a vast network of interconnected joints, fault planes, cavities and solution channels, as well as in the overlying weathered dolomite, chert, wad and aeolian sands. Large quantities of water are stored.
Figure 3. Geohydrological sections through Dolomitic compartments
in the unconsolidated material, in particular where the dolomite has been leached extensively and these materials fill "geological valleys" (figs. 4 and 5), which have been found to extend to depths as much as 200 metres below the surface.

**Figure 4. Geological section through Riebeeck-court, Westonaria**

The ground-water compartments vary in area from a few to more than 250 square kilometres. The storage capacities of the Oberholzer and Venterspost Compartments, two of the larger compartments located above the gold mines, have been assessed at 700,000 and 450,000 megalitres, respectively.

Fractures and fault planes in the Dolomite Series extend into the underlying Witwatersrand and Ventersdorp Systems and thus intersect the gold-bearing reefs. Many of these
fractures, particularly the tension faults, form conduits which, when exposed in the mine workings, discharge water under great pressure from the overlying dolomitic formations. Although the ground water which flows into the mine workings at depths of 1,000 to 3,000 metres below surface is under great pressure, the fracture zones are generally fairly well sealed at those depths due to the high rock pressures and the impervious nature of the strata. The conduits, however, tend to open up as a result of doming, i.e. the settling of the roof and superincumbent rock layers above stoped areas. Doming can result in large increases in the inflow of water and may give rise to sudden inrushes of such volume to overwhelm the pumping facilities of the mine. Although such inrushes in the past have never exceeded 15 megalitres per day anywhere in this field, an unprecedented inrush in the history of mining occurred on the 26th October, 1968, when 365 megalitres per day broke through.

Although cementation has been applied extensively in the mines and inflows have been substantially decreased, the method has not been proved successful for preventing inrushes.

DEWATERING OF COMPARTMENTS

This experience confirms that under certain circumstances it is an unacceptable risk to undermine waterlogged dolomite formations. In the absence of any method of preventing the water from finding its way into the mine workings, there appears to be no alternative but to dewater the dolomite. In 1960 an Interdepartmental Committee, after intensive investigation, recommended that the mines operating in the area accept dewatering of dolomitic compartments as a necessary policy. This recommendation was based on both economic and safety considerations, although it was realised that dewatering would give rise to surface subsidence and the formation of sinkholes in certain areas, and under certain conditions. This policy was accepted and was put into effect.

Dewatering of a compartment entails not only the removal of the water contained in the dolomites, but also the disposal of that water to ensure that it cannot return. Recirculation is thus prevented and this leads to progressive depletion of the water stored in the dolomite and to the drying up of springs, the decrease of inflow into the workings, and saving in pumping costs.

As a result of the implementation of the policy of dewatering the ground water stored in the Oberholzer and the Venterspost Compartments has already been decreased by more than 360 and 320 thousand megalitres, respectively; the ground-water levels have dropped progressively (fig. 6) and the resulting occurrence of slow surface subsidences and sink-
Surface subsidence in the Dolomitic areas of the Far West Rand

Plate 1. Sinkhole at Crusher Plant, West Driefontein Gold Mine

Plate 2. Sinkhole at Blyvooruitzicht
holes imposes a real threat to the development of the Waterfontein Valley and the safety of its inhabitants.

Development of the Wonderfontein Valley as an irrigation farming area started more than 100 years ago. The water supplies were obtained from a number of dolomitic springs, representing the overflows from the dolomitic compartments. When gold mining started, two towns—Westonaria and Carletonville—were established on the dolomite in the valley. At present the populations of these towns are 35,000 and 90,000, respectively. The towns were located in areas where no sinkholes had occurred or subsidences taken place previously and which were considered safe for development. In addition, most of the surface structures of the mines, including offices and crushing and reduction plants were built on dolomite.

It was only as dewatering progressed that instability of the surface became apparent. As a result of subsidences and the possibility of catastrophic sinkholes forming, certain areas were evacuated and many of the mining plants rebuilt on safe areas off dolomite. The direct expenditure in research, application of safety measures, compensation for damage and loss of water supplies and the rebuilding of mining plants on safe areas, has been estimated at R25 million.

When the phenomenon of surface subsidence was first noticed in 1959, it became a matter of urgency that the areas which were subject to subsidence or to the formation of sinkholes be delineated. The real danger to the inhabitants of the area was emphasized when in December, 1962, a sinkhole opened up on the West Driefontein Mine property and engulfed a three-storey crusher plant with the loss of 29 lives (plate 1) and again in August, 1964, when two houses and parts of two other houses disappeared into a sinkhole on Blyvooruitzicht Township with the loss of five lives (plate 2). These catastrophies imposed on the authorities an urgent duty to delineate safe and unsafe areas and to evacuate all suspect areas.

Major research efforts were initiated both by the Chamber of Mines and by the Government into the mechanics of the phenomenon and towards the development of practical methods of delineating safe areas. The Chamber mobilised a team of scientists to investigate direct methods of locating underground voids which could give rise to sinkholes. All known geological and geophysical methods, including magnetic, electromagnetic, resistivity, radio and seismic refraction and reflection methods, were tested. The problem, however, proved too complicated for direct solution by those methods.

The Geological Survey Division of the Department of Mines then turned to the extensive application of gravity methods for delineating potentially dangerous areas. Detailed gravity surveys, supplemented by boreholes drilled for interpretation purposes at strategic points, were carried out and deductions and interpretations were made as to the geological and geohydrological conditions which must pertain concurrently for slow subsidence to take place or for sudden sinkholes to form.

THE NORMAL DOLOMITE SINKHOLES

The occurrence of sinkholes is well-known in most dolomite areas in South Africa. In the course of geological time, the solution and removal of the carbonates of magnesium and calcium by weakly acidic ground water percolating along fissures and fault zones form cavities and channels. Such cavities may be filled with unconsolidated material or may remain empty below a roof of more resistant rock. Should the roof of such a cavity be linked to the surface by a widened fissure, unconsolidated material overlying the dolomite may be carried down into the cavity, leaving a void with an arched and unstable roof. If the equilibrium is disturbed the arched roof collapses and a sinkhole forms (fig. 7).

Observations have proved that, with very few exceptions, such sinkholes are formed as a direct result of abnormal concentrations of water at or very near to the surface, caused
Surface subsidence in the Dolomitic areas of the Far West Rand

After Cal!apie Sinkhole

Dolomitic seriez

Chert a Dolomite

FIGURE 7. The formation of sinkholes by collapse

by broken sewage or water pipes, storm water, leakage from irrigation canals and even by overwatering of gardens. When a new township is being developed conditions are more favourable for abnormal concentrations of water, and sinkholes do in fact occur more frequently.

Such concentrations of water can, however, trigger sinkholes only at points where the following phenomena obtain to create a dangerous situation:

1. There must be a void or cavity into which the roof can fall.
2. The fissure must form a bottleneck of dimensions which can be bridged by a self-supporting arch of the overlying unconsolidated material. The span of the fissure where such conditions develop is seldom more than 10 metres.
3. Depending on the size of the cavity, the solid abutments of the bottleneck must be reasonable near the surface, otherwise the cavity will be filled by volume increase of the caving material and block the cave-in before the surface is reached. The cover of unconsolidated material is generally less than 15 metres.
4. The bridge must be fairly unstable and above the ground-water table, otherwise seepage of surface water will not cause its collapse.

It must be noted that the ground-water or the lowering of the ground-water table plays no part in the triggering of such a sinkhole. In fact, the ground-water table is generally at great depth below the bottleneck which is bridged by the unconsolidated material.

SLOW SUBSIDENCE AND SINKHOLES CAUSED BY DEWATERING

The dewatering of dolomitic compartments by the mines on the Far West Rand gave rise to two separate subsidence phenomena:

Firstly: slow subsidences which take place when the ground water is lowered and compaction of unconsolidated material occurs; and

Secondly: the sinkholes which occur when arches, below the ground-water table but otherwise similar to those which give rise to the normal type of sinkhole, collapse when the structure is weakened by the dewatering.
SLOW SUBSIDENCE

As already mentioned the products of weathering of dolomite—wad, weathered chert, semi-weathered dolomite and other impurities—tend to form a honeycombed structure which has a very low bearing-strength and compacts on being dewatered.

In the Far West Rand the subsurface of solid dolomite which is covered by its weathered products and soil, and often by inliers of younger Karoo beds, is rather irregular and forms an undulating plateau interrupted by geological valleys that vary in depth and width from less than 30 metres to more than 200 metres. These valleys developed mainly as a result of the seepage of ground-water along the numerous post-Transvaal fault planes and the large scale leaching and solution of the dolomite along those zones over millions of years. Consequently the leached zones widened and ultimately became so weak that the overlying layers of rock, the horizons of chert forming the upper horizons of the Dolomite Series, the quartzite and shale of the Pretoria Series and occasionally Karoo sediments slumped into the valleys on top of the honeycombed mass of wad and chert.

These valleys which are generally below the normal water table are, therefore, partly filled with unconsolidated material which, on being dewatered, compact and gives rise to surface subsidence. The degree of subsidence depends on the thickness and percentage of compacting material, which varies laterally, giving rise to differential subsidence, which causes large cracks at the surface. The areas of subsidence can generally be outlined by the very prominent cracks which form along the line where subsiding soil tears away from that on an adjoining stable area. The time lag between the lowering of the water-table and the surface subsidence, where observed, has been fairly short, and the total subsidence in the different valleys has varied from a few inches to more than 30 feet (fig. 8, plate 3). Subsides of one to five feet are very common.

SINKHOLES TRIGGERED BY DEWATERING

A study of the sinkholes which formed in the Far West Rand since mining operations commenced showed very clearly that sinkholes formed concurrently with the lowering of the water table in areas which had been remarkably free from sinkholes before. These areas fall under three groups:
1. Those where the original water table was less than 15 metres below, and less frequently within 30 metres of the surface.
2. The scarp zones bordering on the deep valleys.
3. In narrow valleys, i.e. valleys which are deeper than they are wide. Valleys which are more than 100 metres wide can still be classified as narrow valleys if they narrow down at great depth to a width which permits blockage and bridging of the unconsolidated material to occur. The bridge will be weakened and may collapse when dewatering takes place. Such valleys give rise to sinkholes of larger dimensions than would normally be expected to occur—the largest one has a diameter of 80 metres at the surface, and a depth of 50 metres—thus constituting a much greater hazard. Sinkholes are not formed in wide valleys, i.e. those which are wider than their depth to solid rock, as compaction in this type of valley leads to slow subsidence at the surface.

It has also been observed that sinkholes, which occurred within the geological times and were subsequently filled by aeolian sands tend to redevelop when the bridging at depth collapses (plate 4).

These sinkholes are very often triggered by earth tremors caused by rockbursts in the mines.

DELINEATING POTENTIAL SUBSIDENCE AND SINKHOLE AREAS

From the foregoing it is clear that, in order to delineate those areas which would be subject to slow subsidence or which would be potential sinkhole areas when dewatering takes place, the subsurface contours of the solid dolomite relative to the depth of the original ground-water table, have to be determined.

As the specific gravity of solid dolomite (2.85) is much higher than that of the unconsolidated material which covers the dolomite and which fills the valleys (1.7-2.4) a gravity
The method was considered to hold the most promise and detailed gravity surveys of the compartments which are being dewatered, have been carried out. Bouguer values were calculated and further corrections were applied to eliminate regional anomalies and to reduce the zero gravity contour to correspond to lines along which the subsurface of solid dolomite coincides with the original ground-water table. Positive gravity contours thus indicate areas where the solid dolomite is above the original ground-water table, i.e. areas which will not be affected by dewatering. Negative gravity contours indicate where the original ground-water table is above the solid dolomite, i.e. areas which will be subject to slow subsidence with dewatering; and the zones with the closely-spaced gravity contours indicate the scarps adjoining the valleys.

By more sophisticated analysis and interpretation of the gravity contours it is possible to delineate the zones which are potential sinkhole areas, with fair accuracy. The accuracy of the interpretations is further increased by drilling boreholes at strategic points.

It has thus been possible by the scientific interpretation of data obtained by gravimetric surveys supplemented by boreholes to delineate safe and potentially unsafe areas and to advise accordingly.

It will also be possible to plan any new mining areas where conditions are similar to those encountered on the Far West Rand and thus to kerb the large expenditure on damage caused by subsidence and sinkholes.

**Références**


Intervention of Mr. Owen G. Ingles (Australia):

Question:
Is the gravity method suitable for determining the alignment of proposed roads and railways so as to avoid the possible loss of heavy construction equipment trafficking a potentially cavernous limestone area?

Reply by Dr. Enslin:
Yes, the gravity method has been found very useful for the alignment of roads and railway lines.

The potentially dangerous areas are delineated on the special gravity contour map of the dolomitic area and the safe alignment of the road or railway line can be determined.

It must, however, be noted that because the potentially dangerous zones are closely linked with post-Dolomite fault zones, which may cut right across the dolomitic area, it could be very difficult to route a road or railway line without crossing a danger zone.

Intervention by Dr. Manuel N. Mayuga (USA):

Question:
I notice that you have a substantial loss of lives and properties as a result of subsidence. Do I understand that the mines take responsibility or the liability for all these damage and evacuation and all the liabilities involved?

Reply by Dr. Enslin:
The permits for dewatering the Oberholzer and the Venterspost Compartments were issued by the Department of Water Affairs after agreement had been reached between the Government and the Gold Mines that the Gold Mines concerned would be responsible for paying compensation for financial loss due to loss of water, evacuation of properties, and damage due to subsidence and sinkholes caused by the dewatering.