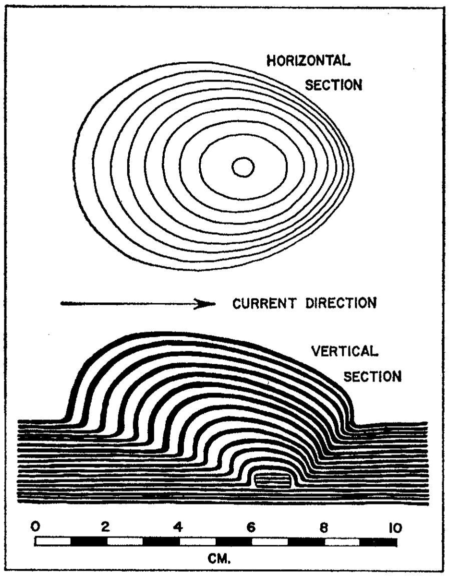

Fig. 3. Idealized horizontal (top) and vertical (bottom) sections of an asymmetric, laterally linked stromatolite, showing the relation of shape to current direction. The thin dark layers represent fine-grained sediment; the clear areas, the coarser-grained layers of sediment. A laminated intraclast serves as a nucleus.

cessive laminations and thus the original relief and morphology of the projection are greatly enlarged and modified (Fig. 3).

Commonly the drape-over lamination surfaces are hemispherical or hemiellipsoidal. In some beds, however, the layers of coarse-grained sediment are thickest of all on the side of the drape-over stromatolite head that faces up-current as indicated by the foreset laminations in ripple-sand lenses in the same bed (Fig. 3). These stromatolites possess an asymmetry related to current trend and sense that is readily seen in outcropping surfaces either parallel or perpendicular to the bedding (Fig. 2).

Stromatolite studies in the Pethei Formation show that (i) single stromatolite beds are continuous for as far as 160 km and are amenable to rock-stratigraphic correlation; (ii) stromatolite shape and orientation may be used to determine paleocurrents; and (iii) stromatolite geometry is controlled at least in part by physical factors of the local environment. Attempts to determine the taxonomic or time-stratigraphic usefulness of stromatolites should therefore be made with caution.

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Sinkhole Formation by Groundwater Withdrawal: Far West Rand, South Africa

Abstract. *Sinkholes up to 125 meters wide and 50 meters deep have developed catastrophically in thick unconsolidated debris above pinnacle-weathered dolomite after lowering of the groundwater surface by at least 160 meters. They are caused by shrinkage of desiccated debris, downward migration of debris into bedrock openings, and upward growth of multiple debris "caverns" by roof spalling.*

Coincident with the beginning in 1960 of a major dewatering program on a portion of the Far West Rand mining district, near Johannesburg, South Africa, many sinkholes were formed, including some that must qualify as the world's largest "man-made" sinks. Between December 1962 and February 1966, eight sinkholes larger than 50 m in diameter and deeper than 30 m have formed.

Subsidence of the ground caused by the withdrawal of fluids from alluvial and weathered debris, as well as from detrital sedimentary rocks, has been measured and described, particularly in the San Joaquin (*1*) and Santa Clara valleys in California and near Long Beach, California (*2*). Within these areas of subsidence, seldom has there been any occurrence of sudden surface collapse. However, within areas of carbonate bedrock, the removal of fluids from the overlying unconsolidated debris has been accompanied by catastrophic collapse and the creation of sinkholes. Although this phenomenon has been described (*3*), it is not well known or understood.

The Far West Rand gold-mining district, situated about 65 km west of Johannesburg, is on a western extension of the reef-bearing Witwatersrand rocks (*4*). A thickness of 900 to 1000 m of Transvaal dolomite and dolomitic limestone unconformably overlies the Witwatersrand system and dips gently south. These are overlain by the Pretoria series of quartzites and shales. All mining on the Far West Rand is done by shafts that must extend through the thick carbonate section.

Deep weathering characterizes the Transvaal rocks where they are not overlain by Pretoria rocks. The depth to bedrock is known to range up to 400 m and commonly is more than 100 m. The ease of movement of groundwater through the dolomites and the remarkably uniform gradient of the groundwater surface, as determined from drill holes, indicates an almost continuous network of interconnected solution cavities within the dolomites. The overlying residual debris includes large unweathered blocks of dolomite and masses of chert ranging at least from 1 to 15 m in diameter. Mixed with the matrix of clay and silt-sized material is considerable soft black manganese oxide.

Cutting across the south-dipping dolomites and shales is a series of thick vertical syenite dikes 35 to 65 m thick and nearly impermeable even in their upper weathered zone. They create essentially watertight compartments that confine the movement of groundwater. The Oberholzer compartment is situated in the middle of the mining district. It includes the town of Carletonville, a number of smaller mining communities associated with three different companies, and ten shafts belonging to the three mines (Fig. 1). Prior to 1960, large springs rose on the upstream side of the dikes and flowed across them

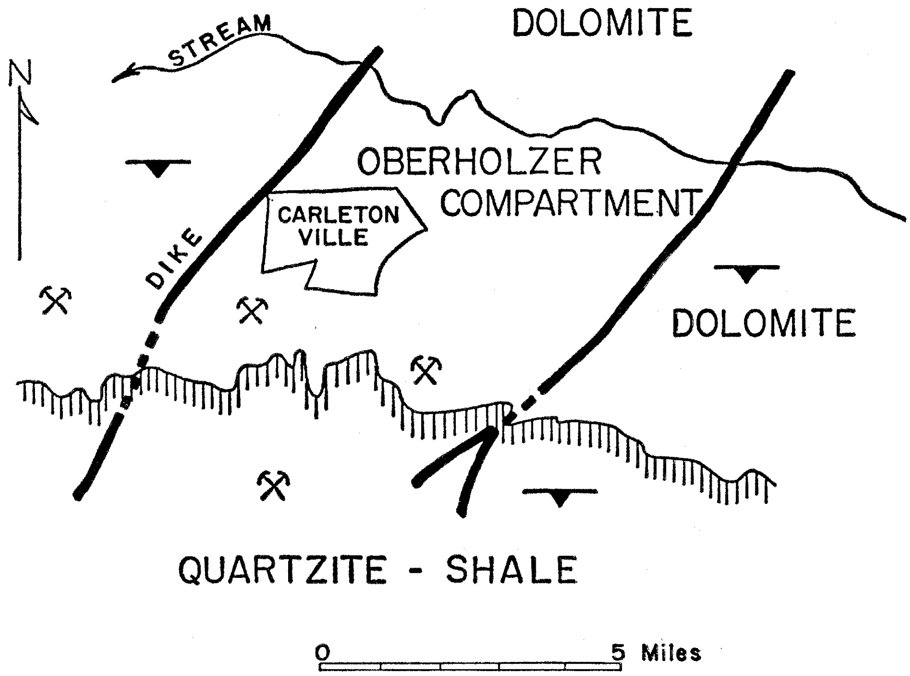

Fig. 1. On the Far West Rand, dolomite, quartzite, and shale strike east to west and dip 20°S. Their contact is shown. Syenite dikes cut across these rocks and make a series of watertight compartments that prevent underground transfer of water from one to another. The major drainage is to the west. Large springs rise behind each of the dikes and flow across them to the next compartment. Four major mines are shown; three of them are in the Oberholzer compartment. Carletonville is the major city (about 100,000 inhabitants).

into the next compartment downstream. The Oberholzer spring flowed with a yield of about 55,000 kl per day, transferring that amount of water across the Oberholzer dike and out of the compartment. A roughly equal amount of water flowed into the Oberholzer compartment from a spring on the upstream side of the eastern (Bank) dike.

In 1960, one of the three companies operating in the Oberholzer compartment began a major program of dewatering. Before this time, the mines were pumped just enough to keep the workings "dry," and the water was discharged on the surface. In 1960, pumping yields were increased, and the water was carried away at the surface in a concrete-lined ditch, ultimately to be discharged outside the Oberholzer compartment.

Groundwater levels declined from about 100 m below the surface in the immediate vicinity of the mines to more than 550 m in July 1966 (Fig. 2). The outer limit of water lowering within the compartment is close to the stream to the north. Groundwater levels in the adjacent compartments were not lowered. A rise of about 3 m has occurred in the downstream compartment.

The Oberholzer spring, located where the stream flows across the Oberholzer dike, ceased flowing in 1960 and has been dry ever since. The stream itself now is dry throughout its course where it crosses the compartment, except for a short distance inside the eastern dike where the water from a spring on the upstream side flows across. This water sinks into the ground almost immediately.

Within a year of the drying of the Oberholzer spring, two kinds of subsidence occurred within the Oberholzer compartment. One was the gradual subsidence caused by compaction of the dried-out unconsolidated debris. The other was sudden collapse of the surface to make steep-walled cylindrical sinkholes.

In most cases, land subsidence can occur only if the bedrock surface is lower than the former groundwater surface and if the unconsolidated debris is "dried out" by lowering of the water surface. One may expect maximum subsidence where there is a maximum thickness of unconsolidated debris and where maximum lowering of the groundwater surface occurs. Two other factors help to account for the difference between the two phenomena and to control which one may occur in specific locations. One of these is the general configuration of the bedrock surface. The other is the presence and location of numerous solution openings within the underlying carbonate bedrock.

A large number of drill holes that penetrate bedrock and an extensive net of gravity survey stations within the

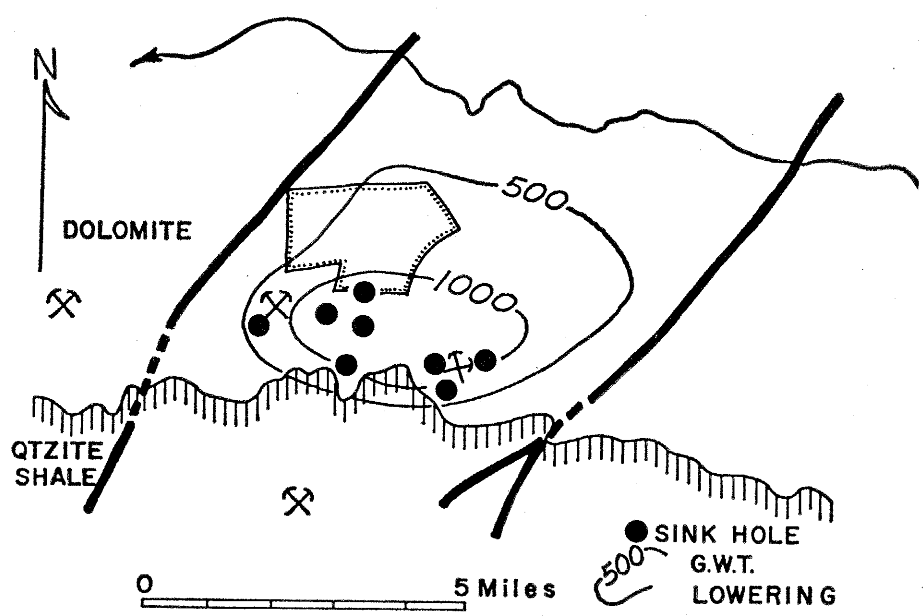

Fig. 2. The 154- and 308-m levels of lowering of the groundwater surface within the Oberholzer compartment are shown as of July 1966. Eight sinkholes larger than 45 m in diameter and 30 m in depth have formed within the area bounded by the 154-m line. *G.W.T.*, groundwater table.

Oberholzer compartment provide the basis for knowing the depth to bedrock in many areas as well as the nature of configuration of bedrock surface.

Locally, the bedrock surface is rather smooth and may exhibit regular "valleys" and "hills." Beginning in 1962, several linear areas of gradual subsidence began to form within the compartment. All of them were within the area of the cone of depression of the lowering groundwater surface, and all were generally aligned with existing areas of lower topography, most of them trending north to south. Characteristic of these linear subsidence areas was a central zone within which subsidence was remarkably uniform and also a zone of shear along the boundaries. In Carletonville, a zone of linear subsidence caused many homes to be lowered as much as 4 m. Those in the center of the zone, which was about 60 m wide, suffered little damage; those on the edge were destroyed. In nearly every instance of linear depressions created by land subsidence, the bedrock surface was much deeper, and compaction of the unconsolidated debris occurred after lowering of the groundwater surface.

Elsewhere, the bedrock surface is very irregular with typical pinnacle weathering and bedrock relief of up to 150 m within horizontal distances of 10 to 20 m. Deeply weathered zones extend downward into cavities (widened by solution) that are sometimes filled with loose debris and sometimes open. Most sinkholes have formed within areas of pinnacle-weathered bedrock, and all of the large ones have occurred there.

In these areas there may be no lowering of the ground surface or only a very small amount of subsidence shortly before catastrophic collapse results in the opening of a steep-walled cylindrical sinkhole. In December 1962, a sinkhole opened under the crusher station adjacent to one of the shafts close to the apex of the groundwater surface that had by then been lowered about 160 m. The sinkhole was about 30 m in depth and 55 in diameter (*5*). There was no warning; 29 lives were lost. In August 1964, another sinkhole of slightly larger dimensions opened in a miners' village in the middle of the night and claimed the lives of a family of five as their home dropped more than 30 m. Three other homes, situated along the edge of the sinkhole, also toppled in within a short period of time, but their residents made dramatic escapes.

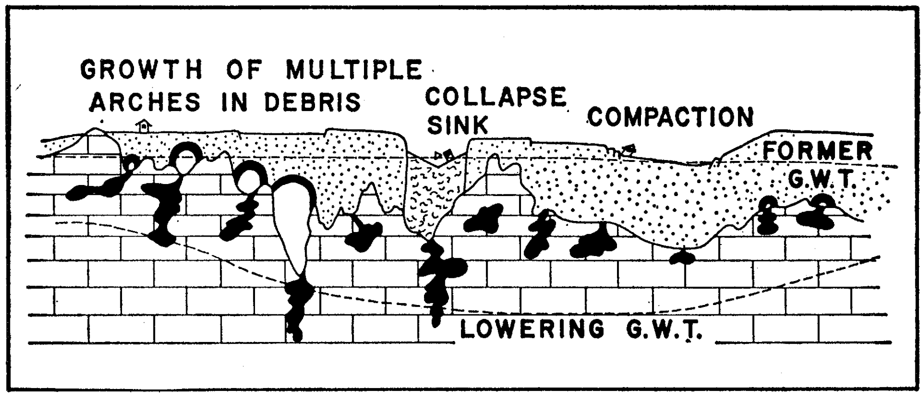

Fig. 3. Lowering of the water table initiates desiccation and downward migration of debris into cavities within the bedrock. Two phenomena result. Subsidence occurs above smooth bedrock areas. Catastrophic collapse occurs above areas of pinnacle weathering.

Figure 2 shows the location of eight large sinkholes and their relation to the lowered groundwater surface. All were formed after lowering of the groundwater surface had reached or exceeded 160 m. Many sinkholes of smaller dimensions have formed and are forming in the outer part of the cone of depression between 60 and 160 m of lowering.

As the groundwater surface is lowered in an area of pinnacle weathering, volume shrinkage due to compaction of the unconsolidated debris takes place. Unlike those areas above relatively smooth bedrock configuration, compaction is irregular or may not be expressed at the surface at all. If the width of a deeply weathered vertical zone between two or more pinnacles is less than about 10 to 15 m, a cavernous opening may develop in the unconsolidated debris, its roof assuming the shape of an arch. The full weight of the overlying lithostatic load would then be carried along the arch and downward through debris abutments against the rock pinnacles. I saw and explored such openings in unconsolidated debris in southeastern Pennsylvania (*6*) and within the Oberholzer compartment.

Dewatering of the unconsolidated debris also causes downward migration of debris into existing openings, widened by solution, in bedrock at greater depth. That there is actual flushing of debris downward into the interconnected openings is well documented by observation of the pumping of "muddy water" in adjacent areas both in Pennsylvania (*7*) and South Africa (*8*). This flushing serves to open space within bedrock into which additional material from above can migrate.

The heterogeneous character of the unconsolidated debris overlying the Transvaal dolomite, with its very wide range of particle sizes, encourages a sporadic but continuous process of roof spalling in debris in the caverns. As spalling occurs, the caverns gradually grow upward, enlarging the vaulted roof. There is some limit beyond which the ability of the arch to sustain the lithostatic load is exceeded. At that moment, rapid upward propagation of the arch by almost continuous spalling results in sudden collapse of the surface. Concurrent rapid downward migration of the spalled debris into underlying interconnected bedrock openings would make it possible for the resulting sinkhole to be larger than it would be if the collapsing debris only filled the already existing opening.

Figure 3 is an idealized sketch to show the general relation of unconsolidated debris above the Transvaal dolomitic rocks, part of the area characterized by pinnacle weathering and part by smoother bedrock. Lowering of the groundwater table has initiated both compaction, with resulting land subsidence, and development of debris caverns, with consequent collapse of the surface.

Several of the largest sinkholes in the Oberholzer compartment formed after there had been rapid seepage of water from the surface. Downward percolating water evidently hastened the process of roof spalling and cavern enlargement, possibly also softening dried debris in the vault abutments. In Febru-

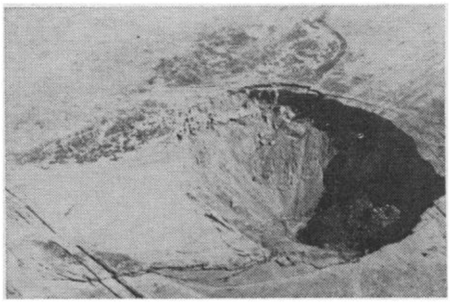

Fig. 4. Giant sinkhole that developed catastrophically early in February 1966. It is approximately 125 m in diameter and 50 m in depth and is located within 0.8 km of a residential section of Carletonville.

ary 1966, the largest of all the catastrophic sinkholes formed near the edge of Carletonville a few days after about 15 cm of torrential rainfall. This sinkhole, measuring nearly 125 m in diameter and about 50 m in depth, occurred "without warning" at the lower (north) end of a linear subsidence area which had developed a year earlier (Fig. 4).

The unusual size of the large sinkholes that have formed makes it difficult to visualize an opening within unconsolidated debris of adequate size to accept all the material at the time of collapse. Experimental studies (*9*) also suggest that a cavity within the debris with a diameter equal to that of the sinkholes that have formed could not possibly support the overlying lithostatic load. I suggest that large sinkholes—and possibly many smaller ones—involve the development of multiple arches between rock pinnacles, close enough to one another so that, as they grow larger, they may suddenly coalesce, thereby increasing the span of the arch beyond its ability to support the load. Experimental studies have shown this not only to be feasible but also to provide the most likely explanation for giant sinkholes (*10*). This would help to explain both the large amount of existing void into which debris could collapse and the rapidity with which the debris moves downward through multiple openings (Fig. 3). After collapse of several of the large sinkholes, continued downward movement of the debris near the base of the sinkhole has been observed.

Withdrawal of fluids from pore space in unconsolidated debris may cause surface subsidence, no matter what the composition of the underlying bedrock. However, catastrophic sinkhole development occurs only if the underlying rocks are carbonates. In addition, bedrock configuration must be highly irregular, typified by pinnacle weathering. If the unconsolidated debris is thick and if there is great lowering of the groundwater surface, then one may expect the development of multiple openings near the base of the mass of desiccated debris. Gradual enlargement of these openings by roof spalling may finally result in coalescence or, at least, a cavity of such size that rapid upward propagation of roof spalls will result in catastrophic collapse of the surface.

Within the Oberholzer compartment on the Far West Rand, South Africa, extensive observations of sinkhole development support the suggestion that sinkholes begin to form when the groundwater surface has been lowered 30 to 60 m. The eight giant sinkholes formed after the groundwater surface had been lowered approximately 160 m. As the area of the cone of depression of the lowering groundwater surface has expanded, the occurrence of sinkholes has increased and has moved outward from the center of the cone.

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10. At my suggestion, Dr. Knight prepared model experiments that showed the development of multiple arches with consequent giant sinkholes.
11. I thank the staffs of the Orange Free State and Transvaal Chamber of Mines, Goldfields of South Africa, Ltd., Anglo-American Corp., and Rand Mines, Ltd. Thanks are also due to J. Irving and J. L. Prince for their help in the field investigations.

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Echinoderm Calcite: Single Crystal or Polycrystalline Aggregate

Abstract. *Electron microscopy of natural and broken surfaces of echinoid skeletal plates reveals that the interior portions have the morphology of a single crystal, whereas the exterior is a polycrystalline aggregate with preferred orientation. These data help to resolve earlier contradictory x-ray and optical evidence.*

The skeletal elements of most echinoderms consist of a fenestrate latticework of calcite, and in the living animal this stereom is interpenetrated with mesodermal tissue. The calcite frequently contains significant $MgCO_3$ in solid solution. Each skeletal element behaves as a single crystal in polarized light. An important exception to this are the spine-bearing tubercles in some species of echinoids. Raup (*1*) has summarized much of this information concerning the nature of the echinoderm endoskeleton; and, on the basis of his own optical studies, he has demonstrated that the *c*-axes show a preferred orientation in the individual skeletal elements that is related to the morphology of the echinoid. The optical homogeneity combined with their porous and irregular geometry has often raised the question of whether the skeletal elements are single crystals or highly oriented polycrystalline aggregates. The evidence is contradictory, although the majority of it points to the single-crystal structure. All optical work in polarized light suggests a single crystal, whereas the x-ray data are in disagreement. West (*2*) using an echinoid spine concluded from Laue patterns that each spine was a single crystal. Donnay (*3*) reached a similar conclusion. However, Garrido and Blanco (*4*) and Nissen (*5*) interpreted their data to mean that each skeletal element is constructed of tiny crystallites in almost-perfect parallel orientation. Currey and Nichols (*6*), working with scanning electron microscopy, appear to have confirmed the data of those favoring a single crystal. From conventional electron microscopy, I now offer evidence that helps to resolve this conflict.

Adult specimens of the regular echinoid *Strongylocentrotus droebachiensis* (Müller) from Eastport, Maine, were provided for study by P. M. Kier and T. F. Phelan, of the U.S. National Museum. The dried skeletons were placed in Clorox and vacuum-soaked