The stability of the strata overlying the mined-out areas of the central Witwatersrand

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SYNOPSIS

The paper reviews the restrictions imposed by the Department of Mines (now the Department of Mineral and Energy Affairs) on the surface use of ground that has been undermined at shallow depths (down to a depth of 244m). The reasons for the restrictions are discussed, with special reference to the early records kept by the Department of Mines on subsidence and fracture of the surface. A discussion of the nature of the strata overlying the ore-body, and the effect of undermining, is followed by a detailed accout of investigational work, particularly since 1970, on the stability of shallowly undermined ground.

The significance of the data collected during the investigations is considered next, with special reference to the social and economic implications. These are so far-reaching, that it is proposed that the already flexible approach of the Department of Mineral and Energy Affairs in considering what structures may be built on undermined ground should become even more flexible. To this end, the appointment of a Commission is proposed to collect as much information as possible on the stability of ground undermined at shallow depth, and to revise the current over-restrictive conditions or guide lines that are in use.

SAMEVATTING

Die referaat gee 'n oorsig oor die beperkings wat die Departement van Mynwese (tans die Departement van Mineraal- en Energiesake) gelê het op die oppervlakgebruik van grond wat tot naby die oppervlak ontgin is (tot 'n diepte van 244m). Die redes vir die beperkings word bespreek met spesiale verwysing na die vroeë rekords wat die Departement van Mynwese van die insakking en breuk van die oppervlak gehou het. 'n Bespreking van die aard van die lae wat oor die ertsliggaam lê en die uitwerking van ontginning tot naby die oppervlak word gevolg deur 'n uitvoerige verslag oor ondersoekwerk, veral sedert 1970, in verband met die stabiliteit van grond wat tot naby die oppervlak ontgin is.

Die betekenis van die data wat tydens die ondersoek versamel is, word vervolgens oorweeg met spesiale verwysing na die sosiale en ekonomiese implikasies. Hierdie implikasies is so verreikend dat daar voorgestel word dat die Departement van Mineraal- en Energiesake se benadering by die oorweging van strukture wat opgerig mag word op grond wat tot naby die oppervlak ontgin is, wat reeds buigsaam is, nog meer buigsaam behoort te word. Met die oog hierop word daar voorgestel dat 'n kommissie aangestel word om soveel moontlik inligting oor die stabiliteit van grond wat tot naby die oppervlak ontgin is, in te win en die huidige te beperkende voorwaardes of riglyne wat gebruik word, te hersien.

Introduction

Early in 1970, the writer was asked to report on the stability of certain building sites in the southern business sector of Johannesburg that had been undermined in the early days on both the South Reef and the Main Reef Leader horizons. The owner of the ground wanted to erect a multistorey building, but was unable to do so because of restrictions of the Department of Mines. (Although the Department is now known as the Department of Mineral and Energy Affairs, it is referred to in this paper by the name it bore at the time of the occurrences recounted.)

These restrictions have had, and continue to have, a profound effect on land usage and development. The general restrictions in force at the time are shown in Table 1.

TABLE 1

DEPARTMENT OF MINES' RESTRICTIONS IN 1970

Undermined depth		Building permitted
Feet	Metres	
0 – 300	0 – 91	No building to be erected
300 – 400	91 – 122	One-storey buildings only
400 – 500	122 – 152	Two-storey buildings only
500 – 600	152 – 183	Three-storey buildings only
600 – 700	183 – 213	Four-storey buildings only
700 – 800	213 – 244	Five-storey buildings only

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The owner had hoped that a detailed investigation, and the recommendation of support measures in the stopes below the proposed building, would persuade the Department to waive its restrictions. In the event, permission was granted for the erection of a twenty-storey building, but only on condition that adequate supports were put in the stopes to a depth of 35 m below the foundation of the building.

This investigation fired the writer's interest in the subject, and he obtained permission from the Government Mining Engineer to examine the records at the Department of Mines dealing with undermining strictures and subsidences. This examination revealed that very few facts were available on past or current subsidence rates, and that the records contained very little technical discussion on such questions as how or why undermined strata subside and fracture, or on the competence of the quartzites. He therefore considered that the time had come to obtain more factual data on the behaviour of strata that have been undermined.

Restrictions from 1893 to the Present

In the *Staats Coerant* of 7th June, 1893, there was published 'Wet No. 3 – Myn Regulasies', an Act that included Regulation 1(2) which was headed 'Maatregelen voor de veiligheid van den bovengrond' (Regulations for the safety of surface areas). This general act laid down the conditions for mining under surface areas where there were rivers, roads, railways, building sites, and constructions that might be affected if unrestricted mining were allowed. There is no reference to restrictions on the building of roads, railways, houses, and other constructions *on ground that had already been undermined.* This omission is understandable: so little mining had been done by that date, that the problem of erecting structures on undermined ground had not yet arisen.

No records were to be found in the Department of Mines dealing with undermining permissions during the years 1893 to 1910. This prompted the Government Mining Engineer to write a letter, in March 1979, to the Chief Archivist to enquire whether he had any such records in his archives. The reply was that no such records could be traced. Consequently, the writer concentrated his studies on undermining matters dealt with by the Department of Mines from 1910 onwards.

It is important to appreciate that this paper does not concern itself with the strictures placed by Regulation 2 of the Mines and Works Act on *mining* under a surface that has for some or other reason to be kept stable. It is concerned solely with the strictures that have been imposed *on the use of ground that has already been undermined* – strictures that seem to be based on instructions from the Department of Mines and not on any regulation in the Act.

A perusal of the available documents soon made it clear that, while there were numerous reports dealing with permissions to mine under existing surface structures, there were singularly few references to restrictions when requests were made to construct, for example, roads, railways, or buildings on undermined ground. The first evidence that the Department was concerned with the surface use of ground already undermined was a memorandum dated 30th October, 1946, which had been prepared by the survey staff of the Department and was entitled 'Undermining – Permissions in Terms of Regulation 2 of the Mines and Works Act'. This dealt almost entirely with the conditions that should apply to mining under existing surface installations.

However, section 5 of the memorandum contained provisions for 'Building on Undermined Ground'. Its main provisions were of a very general nature, and were summarized, on page 12 of the memorandum, as follows.

(a) As a general rule, no dwellings or buildings where people are likely to congregate are permitted.
(b) All buildings are restricted to single-storeys and the height of any wall is not to exceed 17 ft (5 m).
(c) In all cases, the foundations are to be of reinforced concrete.
(d) The building is only to be used for the purpose specified.

Early in 1965, the Deputy Government Mine Surveyor stated that the 1946 memorandum as revised was the 'last and only memorandum drawn up in connection with the primary requirements for undermining or building on undermined ground'. However, it was apparently felt by the Department that a 'revised and modernised version to clarify the position was long overdue'.

Later that year, the Government Mining Engineer approved a memorandum that contained recommendations outlining the special conditions that should apply to grants for surface rights, industrial stands, and townships on proclaimed land. The suggested conditions framed for insertion in grants were as follows.

(1) As this erf (stand, land, etc.) forms part of land which is, or may be, undermined and liable to subsidence, settlement, shock and cracking due to mining operations past, present or future, the owner (applicant, grantee, etc.) thereof accepts all liability for any damage thereto or to any structure thereon which may result from such subsidence, settlement, shock or cracking;

(2) (a) no building shall be erected from ten feet on the footwall side of the lower face-trace of the outcrop to where the hanging-wall of the shallowest economic reef is 300 ft [91 m] below surface;
(b) no buildings where persons sleep or congregate shall be erected where the hanging-wall of the shallowest economic reef is from 300 ft to 800 ft [91 to 244 m] below surface; places where people sleep or congregate would include boarding houses, hotels, dwellings, churches, schools, grandstands, theatres and large departmental stores;
(c) main buildings referred to in (f) shall be constructed of reinforced concrete framework with panels of suitable type; or wood or steel framework clad with sheets of corrugated iron or asbestos, or other suitable material of similar type;
(d) small outbuildings may be built of brick, stone, concrete blocks or similar material and are limited to one storey;
(e) the heights of the walls of the main buildings shall be measured from the mean ground level of the stand and shall include such parapets as may be built;
(f) the heights of walls of main buildings shall be as follows.

Depth of reef		Storeys	Height of walls	
Feet	Metres		Feet	Metres
0–300	0–91	Nil	—	—
300–400	91–122	One with basement level	16	4,8
400–500	122–152	Two with one basement level	27	8,2
500–600	152–183	Three with one basement level	38	11,6
600–700	183–213	Four with one basement level	49	14,9
700–800	213–244	Five with one basement level	60	18,3

Where the depth of the reef exceeds 800 ft [244 m], no building restrictions need be enforced, except where excessive stoping widths exist, or when the Inspector is of the opinion that very severe shocks or tremors may seriously damage the building to be erected.

In several subsequent memoranda dealing with buildings on undermined ground, reference is constantly made to the fact that no hard-and-fast rules can be laid down in regard to the restrictions relating to any particular site. The following excerpts from the memoranda bear witness to this flexible approach.

> No matter what the surface object is, each application must be treated on its own merits.
>
> . . .
>
> It must be appreciated, however, that owing to varying conditions, it is impossible to standardise completely, as each case must of necessity be treated on its own merits.

Of interest are the reasons for the restrictions, and how it came about that the Department of Mines was in a position to specify a range of depths to which different restrictions should be applied. It is believed that one of the 'reasons' is to be found in the ground movements that occurred on the central Rand when mining was in progress in the upper levels of the mines, i.e., at depths ranging from surface to 244 m.

The Reasons for the Restrictions

In searching among the files in the Government Mining

Engineer's Department for information on surface subsidence, the writer had the invaluable assistance of Mr W. H. Cable, until recently the Head of the Department's Survey Section, who found a file entitled 'Duplicate File used in S.A.R. vs S.O.J. Case (GME 2593/1906)'. The file contained records of the subsidences that had occurred on the central Witwatersrand during the years 1903 to 1914. These records, which consist of extracts from the Government Mining Engineer's annual reports, and include 32 diagrams illustrating the locality and extent of surface disturbances due to mining, give a clear picture of the 'subsidence situation' during those years.

Examples of such subsidences on three mines are given below. All the diagrams were reproduced from the original reports.

Durban Roodepoort Deep. Figs. 1 and 2 show a portion of the underground workings at Durban Roodepoort Deep

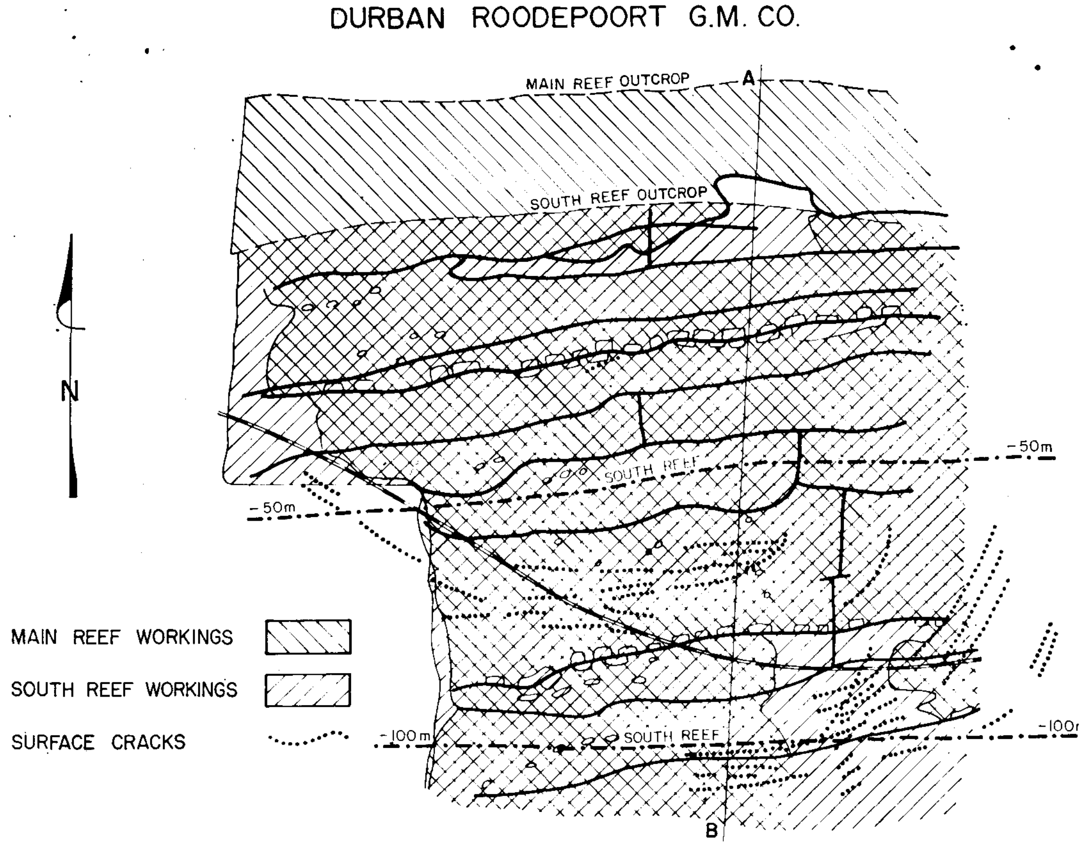


Fig. 1—Plan of the underground workings at Durban Roodepoort Deep, showing the positions of surface cracks

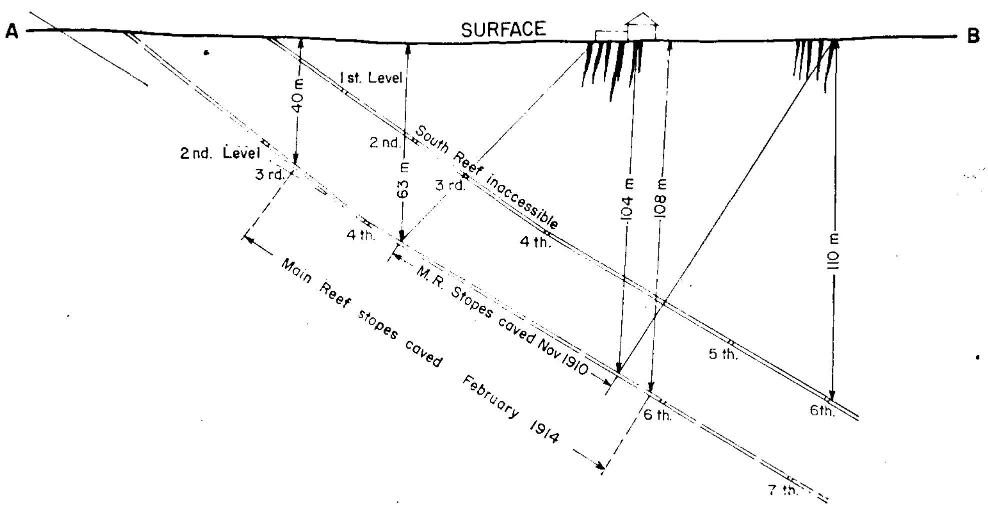


Fig. 2—Section through A–B of Fig. 1, showing the depth of the workings and the positions of the surface cracks

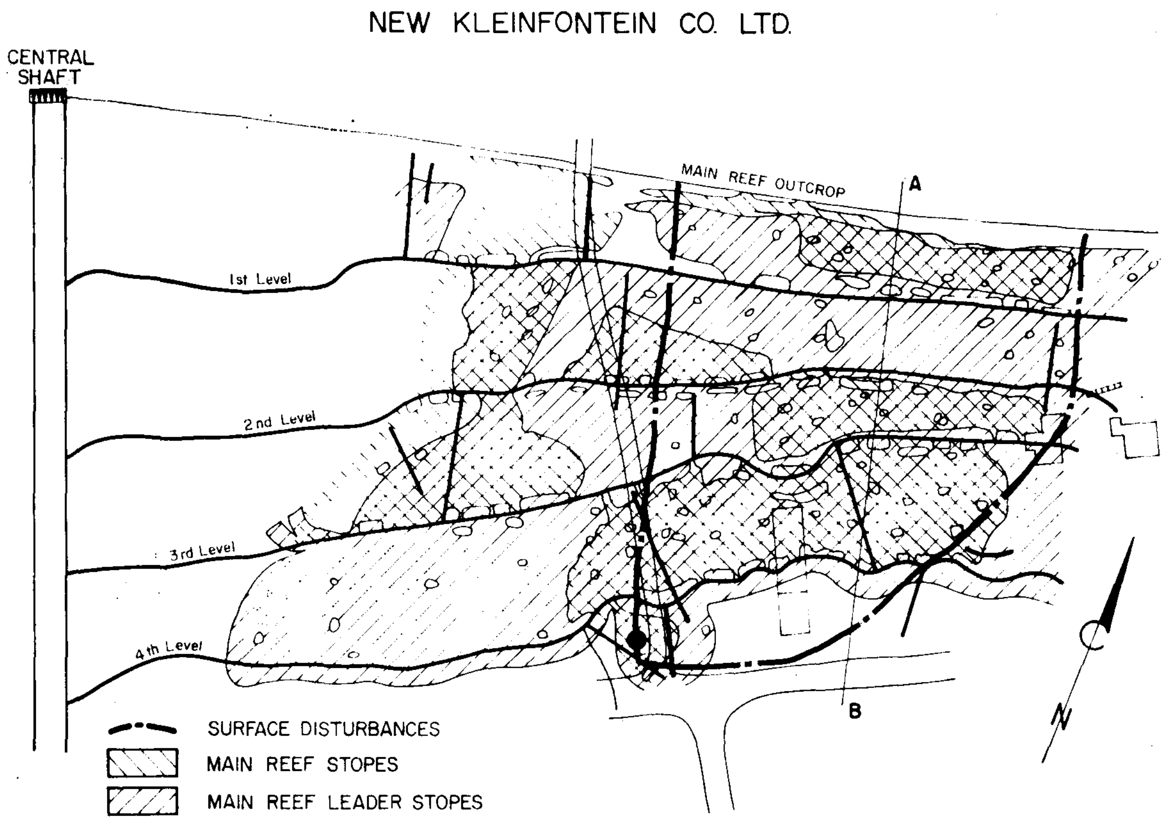


Fig. 3—Plan of the underground workings at New Kleinfontein, showing the positions of surface disturbances

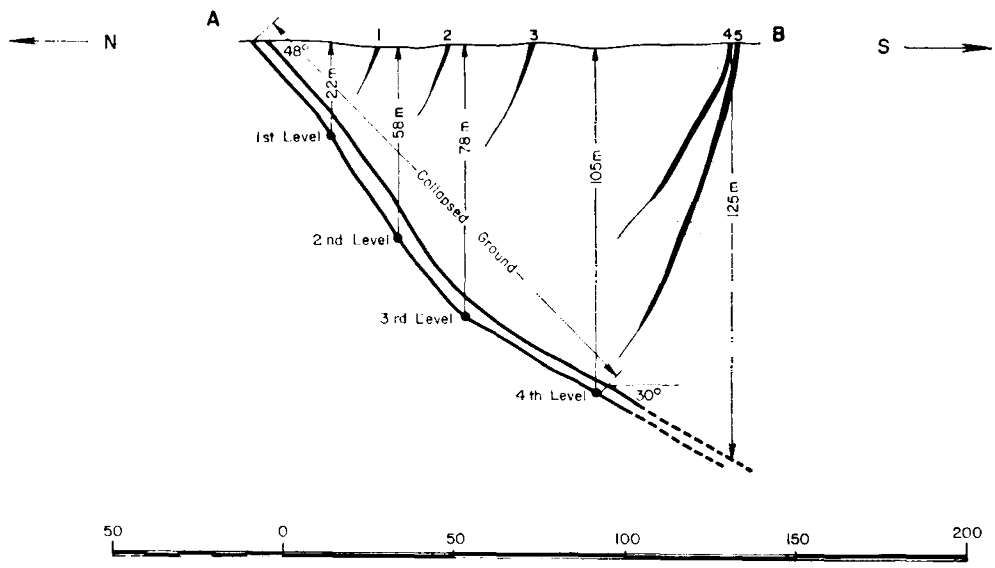


Fig. 4—Section through A–B of Fig. 3, showing the depth of the workings and the positions of the surface cracks

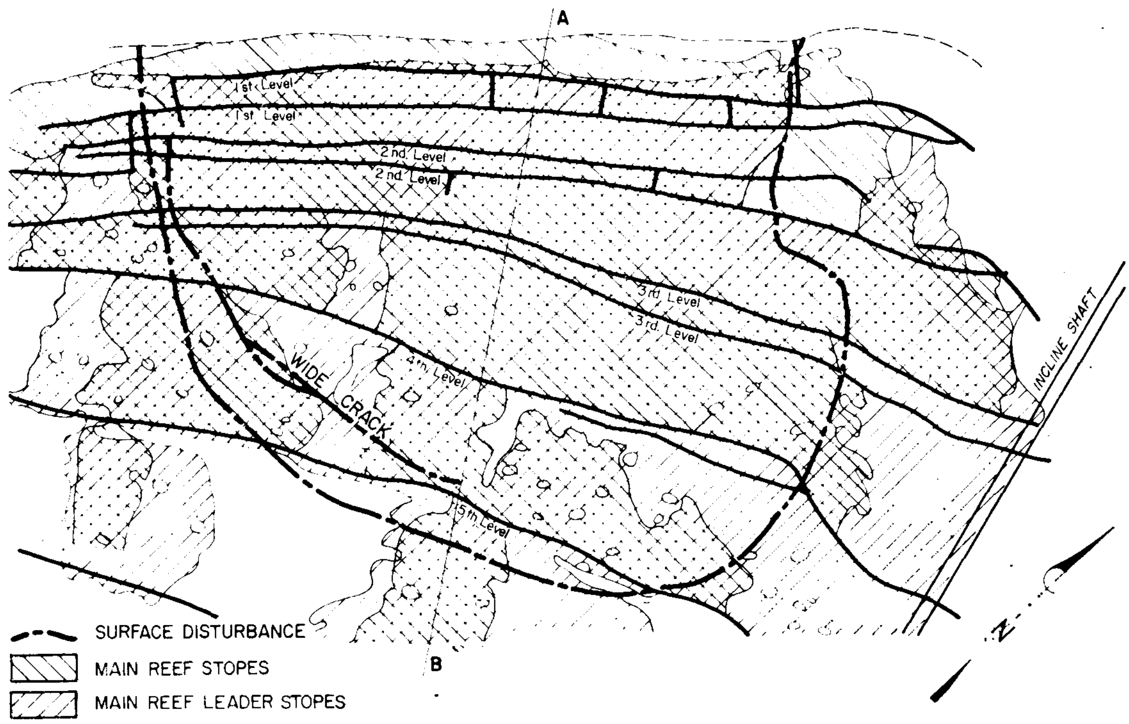


Fig. 5—Plan of a portion of the underground workings at Van Ryn Gold Mines Estate in relation to the zones of surface disturbance

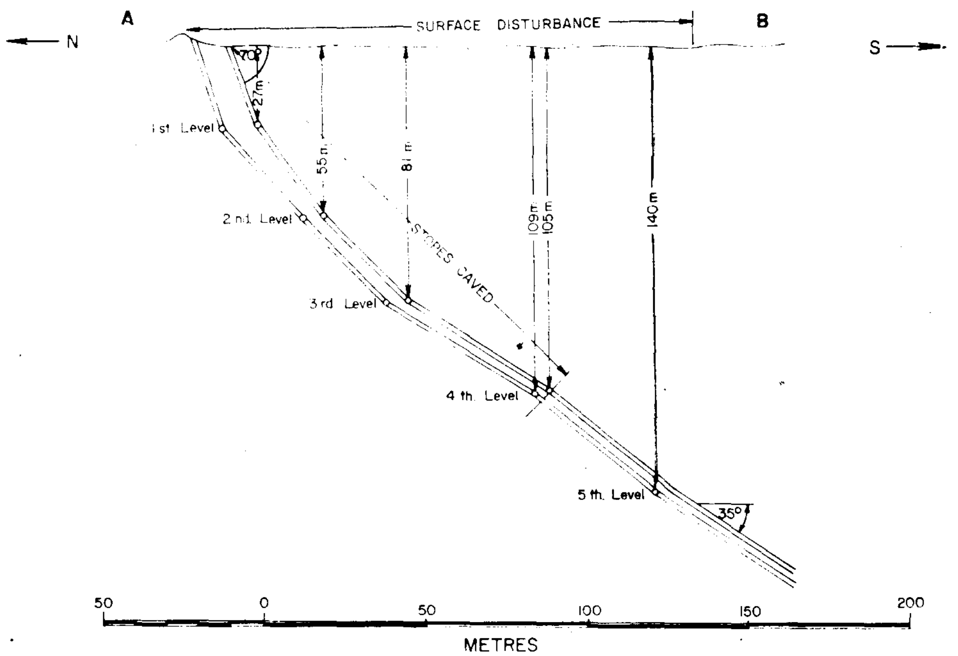


Fig. 6—Section through A–B of Fig. 5, showing the depth of the workings

in the Roodepoort District (20 km west of Johannesburg) in February 1914. The report on the subsidence reads as follows:

> In February 1914 a collapse took place in the stopes and caused a number of cracks on surface with widths in some places of as much as 3½" [90 mm]. There are signs along the affected zone of settlement greater than 1" [25 mm]. The ground . . . . appears to have moved northwards to the extent of 3½" [90 mm] as evidenced by the pulling apart of the flooring boards of a store which had been affected by the cracks.

New Kleinfontein. Figs. 3 and 4 show a plan and section respectively of the underground workings at the New Kleinfontein Mine (in the Benoni district, 30 km east of Johannesburg) as at July 1906. These successive surface cracks occurred as the working depths increased. To be noted is the decrease of dip with depth.

Van Ryn Gold Mines Estate. Figs 5 and 6 show a portion of the underground workings at Van Ryn Gold Mines Estate (in the Benoni district, 30 km east of Johannesburg) in 1910. It can be seen that the disturbed surface relates strongly to the shape of the mined area. Of special interest is the following statement:

> Numerous cracks were formed — one being 2 ft to 3 ft wide along a considerable portion of its length.

Here there is evidence of horizontal movement, i.e., of the surface fracturing because of tension stresses. Again to be noted is that the dip of the reef decreases with depth.

A feature of the cracks on these three mines is that they apparently occurred non-violently. Throughout the Government Mining Engineer's reports where these deal with subsidence, there is not a single reference to sudden failure or rupture of the strata. Indeed, the reverse is true, for, in the Government Mining Engineer's reports of 1920, 1921, and 1923 respectively, the following appear:

> at Geldenhuis Deep Mine cracks opened up to 1½" [38 mm] over a period of 6 months [1920].
>
> at New Kleinfontein there was a gradual opening up of cracks from 3" [76 mm] to 6" [152 mm] over a period of 7 months [1921].
>
> at Van Ryn Gold Mines cracks opened up in 6 months to 1½" [38 mm] [1923].

The above are but a few examples of what would seem to justify the Department of Mines' conservative approach to the use of ground that has been undermined. They are, however, not the only justification: the walls of outcropping stopes often break away and plunge down into old workings, leaving dangerous-looking caverns or voids. Such caverns are shown in Figs. 7 to 16.

The vertical reef outcrops are particularly suspect, especially if the footwall is of shale, which weathers more easily and is much weaker than the hangingwall quartzites (Figs. 15 and 16). Problems regarding the stability of the surface near the outcrop of the reefs also arise where the dip of the reefs is small (20°) and several reefs have been mined. This fact is well illustrated in Fig. 15, which shows the fractured hangingwall overlying the NA 1 and Main Reef Leader stopes. Small wonder, then,

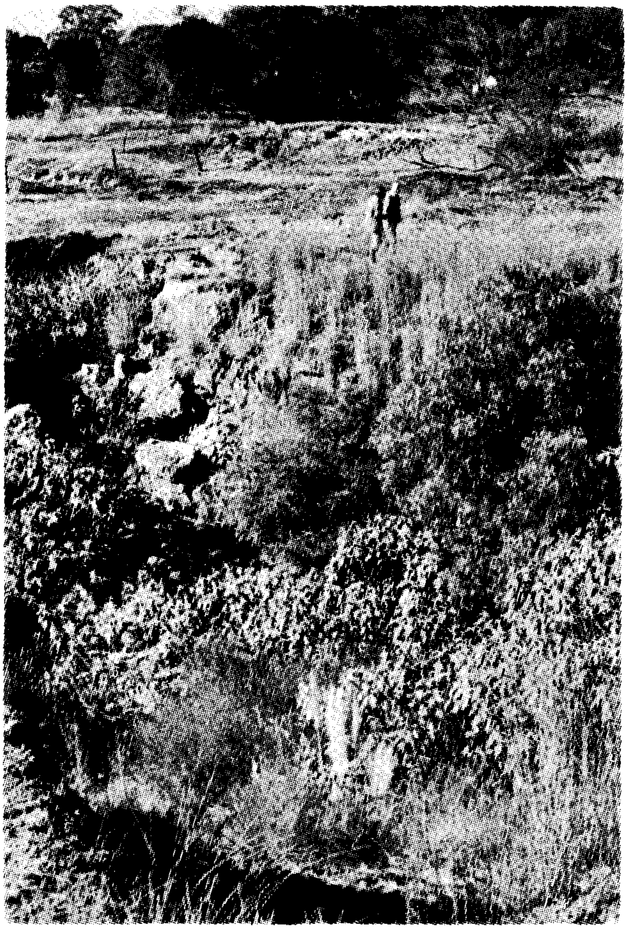


Fig. 7—Collapsed hangingwall at an outcrop of the reef, Waverley Mine

Fig. 8—Surface crack in the hangingwall of the reef outcrop shown in Fig. 7

Fig. 9—Caved outcrop workings on Portion 20, Rietfontein Consolidated

Fig. 10—Surface crack in hangingwall of the outcrop reef shown in Fig. 9

that the Department of Mines insists on a thorough investigation of any outcrop site where it is proposed to use the surface – whether it be to lay a sewer, build a road or railway, or erect a building. It should be pointed out, however, that the happenings at the actual outcrop have little bearing on the stability of ground, say, 50 or more metres to the south of the outcrop, i.e., depending on the dip.

The question next arises as to how the Department of Mines came to specify so closely the relationship between the depth of undermining and the surface usage, e.g., the allowable heights of buildings. In particular, how did it come about that restrictions ceased when the mining depth exceeded 800 ft (244m)? In the hope of throwing some light on these questions, the writer studied the data in file GME 2593/1906, as well as the Government Mining Engineer's annual reports from 1903 to 1979, and compiled Table II, which gives for a large number of mines the positions of the most southerly cracks in relation to the mining depths. The approximate location of these mines and the dips of the outcropping reefs are shown in Fig. 17. It should be noted that the mines cover a distance on strike of some 70 km, and that the dips vary greatly – from 16° at Simmer and Jack to 87° at Ferreira.

From personal knowledge, the writer is aware that pre-1927 subsidences occurred on a more massive scale, and surface fractures were far more frequent, than would appear from Table II, which does, however, give a reasonably reliable picture of the effect of shallow-depth mining on hangingwall strata.

An analysis of the data reveals that the Government Mining Engineer reported surface cracks on 32 mines at positions where the undermined depth was less than 800 ft (244 m); this compares with only 6 occurrences where the depth of undermining was greater than 800 ft (244 m), despite the fact that by 1927 a substantial amount of deep-level mining had already taken place, i.e., from 244 to 1800 m below surface. Table II shows very large subsidences at some of the mines; for example, 3 ft (815 mm) at C M R and 4 ft (1220 mm) at Simmer and Jack. The reason for such large subsidences is not far to seek – the combined stoping widths of the reefs went up to as much as 15 ft (4600 mm)! Unfortunately, there was no sustained, systematic monitoring of surface settlement during this pre-1927 period. Nevertheless, the records give a sound reason for the Department's decision to apply the 'cut-off' to building and other restrictions where the depths of undermining exceeded 800 ft (244 m). It was based on facts that showed that, with shallow-depth mining, the surface could be so seriously disturbed by subsidence and fracture of the strata that damage to structures was a strong possibility.

Fig. 11—Outcrop of a vertical reef, Van Ryn Estates

Fig. 13—Extensive collapse of sidewalls of a stope, Van Ryn Estates

From 1927 onwards, there is virtually no mention in the Government Mining Engineer's annual reports of surface disturbances due to mining; the phenomena of visible subsidence and fracture had decreased to such an extent that they no longer merited recording and comment. We might say, indeed, that the end of an era had been reached – an era when shallow-depth mining had been at its peak and surface effects widespread and pronounced. It was an era of down-dip mining via winzes and incline shafts, the stope-faces moving deeper and deeper, and forming a 'strike' front-line with the solid ground, thus providing a fulcrum to the subsiding ground with resultant tension cracks on surface. With the passage of time, the shallowly mined ground gradually settled down; the pent-up stresses in the hangingwall strata had been released, leading ultimately to a state of stability and safety. (This statement is not based on surmise but on investigations carried out during the past twenty years on the behaviour of the surface under which mining has long since ceased and where the depths of undermining are less than 244 m.)

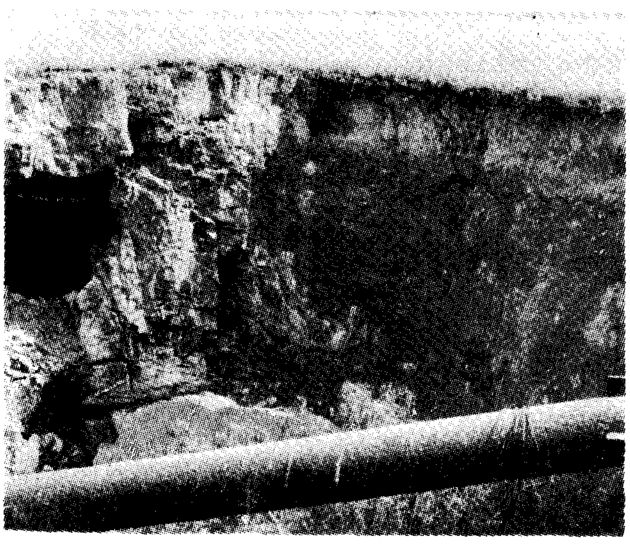


Fig. 12—Collapse of sidewalls of an outcrop stope, Van Ryn Estates (note unsafe bridge above the stoped area)

This summary of the early records showing the effect of mining on surface stability is a recital of facts; no attempt was made in the Government Mining Engineer's reports to illustrate the mechanisms of subsidence and fracture, and to describe how, and explain why, the strata subside and fracture. As a clear understanding of the factors that affect surface stability requires a knowledge of the nature of the hangingwall rock and its behaviour when undernined, these matters are discussed in the next two sections.

Fig. 14—Widening of stope due to slabbing away of hanging-wall and footwall rock, Van Ryn Estates

Nature and Competence of the Hangingwall Strata

Since 1970, a number of diamond-drill holes have been put down at different sites on the central Witwatersrand to show the depth to the stoped-out reefs, the depth of weathering of the hangingwall quartzites, and the strength or competence of the quartzites. Table III gives the results obtained.

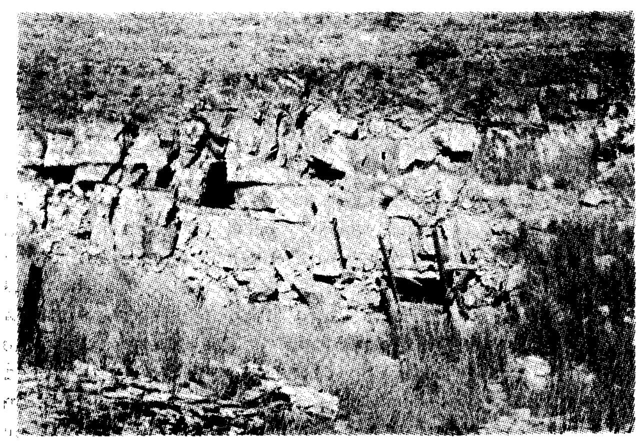


Fig. 15—Fractured hangingwall overlying worked-out stopes, New Modder

Fig. 16—Sinkhole in the hangingwall strata shown in Fig. 15

It will be noted that, from the Riverlea site to Westgate Station, the depth of weathering ranges from 35 to 57 m, the average depth being 46 m. Further east, at the Rietfontein Consolidated Mine, the depth of weathering is much less, the range being 18 to 38 m and the average 32 m.

Fig. 18 gives the logs of boreholes RL2, BHB, and DD2, one borehole having been selected from the west, the centre, and the east of Johannesburg respectively (Table III). These describe broadly the nature of the strata overlying the reefs. It will be noted that, above each of the stopes intersected by the boreholes, there is a zone of rock that has been fractured; actual gaps in the hanging were not found, though these may have developed during the stoping period, only to be closed again as the main rock mass settled and compacted the fracture zone.

The picture that emerges is of a highly competent quartzite rock above the reefs in both the weathered and the unweathered zones; rock with even the lowest recorded compressive strength of 22 000 kPa is suitable for the erection of a multistorey building provided that there is no danger of differential movement.

Effect of Mining on the Hangingwall Strata

There are four forms of subsidence and fracture that occur in the critical zone under consideration – the zone extending from surface to a depth of 244 m.

Collapse at the Outcrops of Reefs

The sudden collapse of surface material into old mine workings (or 'outcrop sinkholes') is not uncommon in the Johannesburg area, and during the past ten years at least a dozen have occurred, e.g., at the Ferreira parking ground, at a point just north of Westgate Station, at the southern end of Smal Street, and on the Main Reef Road near the old Wolhuter Mine. A feature of these surface collapses is that there is no time limit to their occurrence;

TABLE II

SURFACE CRACKS AND SUBSIDENCES ON THE CENTRAL WITWATERSRAND GOLD MINES AS RECORDED IN THE GOVERNMENT MINING ENGINEER'S ANNUAL REPORTS

Year	Name of mine*	Depth below surface of the South Reef at the position of most southerly crack		Observations recorded	
		Feet	Metres	Subsidence	Cracks
1903	Pioneer-Bonanza	550	168		
1903	May Consolidated	680	207		
1903	New Heriot	640	195		
1905	Treasury and Jumpers	440	134		
1905	Cham' Or and French Rand	840	256	3" – 6" (75mm–150mm)	Crack 2" (25mm) wide
1906	Windsor	440	134	4" (102mm)	Crack 2" (25mm) wide
1907	New Kleinfontein	410	125		
1908	May Consolidated	680	207	1" (25mm)	Crack 1½" (38mm) wide
1908	York	140	43		
1908	Langlaagte Estate	930	283		
1909	New Primrose	690	210		
1909	Geldenhuis Estate	280	85		
1909	Geldenhuis Est. and Treasury	500	152		
1910	New Goch	530	162		
1910	Van Ryn G M Estate	460	140		Cracks up to 36" (915mm) wide
1910	Durban Roodepoort Deep	350	107		Cracks 1" (25mm) wide
1911	East Rand Proprietary Mines	601	183		Many cracks 1" (25mm)
1912	East Rand Proprietary Mines				
1912	Consolidated Main Reef	470	143	36" (915mm)	Many cracks 1" (25mm)
1912	Simmer and Jack	500	152		
1913	Ferreira Deep	1500	457		
1914	Durban Roodepoort Deep	360	110		Cracks up to 3½" (90mm)
1914	Van Ryn G M	315	96		Numerous cracks up to 12" (305mm) wide
1915	Rose Deep	982	299		2 surface cracks 1"–2" (25mm to 50mm)
1916	Durban Roodepoort Deep	720	220		Cracks up to 2½" (65mm)
1917	Geldenhuis Deep	120	37	Subsidence	Numerous cracks up to 3" (75mm)
1918	Simmer and Jack Mines	590	180	Subsidence up to 4 ft (1220mm)	Numerous cracks up to 1½" (38mm)
1919	Wolhuter and City Deep	570	174	2½"–18" (65mm–450mm)	
1919	West Rand Consolidated	280	85		Two well-defined cracks up to 6" (150mm)
1920	Geldenhuis Deep	375	114	Levelling showed subsidence since 1912 of 13½" (350mm)	
1920	Wolhuter	1500	457		
1921	New Kleinfontein	240	73		Cracks 3"–6" (75mm–150 mm)
1923	West Rand Consolidated	200	61	No subsidence along cracks but area as a whole subsided 18" (450mm)	Cracks up to 4" (100mm)
1923	Van Ryn Gold Mines	800	244		Some cracks 1½" (38mm)
1926	East Rand Proprietary Mines	330	101		
1926	New Pioneer Central Rand Mines	250	76	Drop south of crack up to 14" (355mm)	Cracks 9" (230mm)
1926	Randfontein Estates	1000	305		
1927	New Pioneer Central Rand Mines	300	91	6" (150mm)	
1927	New Primrose G M Co	480	146		Cracks of varying width

*The locations are shown in Fig. 17.

the seemingly firm material filling the voids at the outcrops may be weakened after a considerable number of years by percolating waters, or timber supports may rot and no longer form an adequate support. These outcrop areas are therefore always suspect and, wherever structures such as roads, railways, sewer lines, or buildings have to straddle or are sited immediately adjacent to them, full precautions should be taken against the danger of collapse.

Apart from the formation of sinkholes, the outcropping reefs, particularly if steeply dipping, may present other surface problems. The nature of these problems is illustrated by Figs. 7 to 16, which show examples of the large, dangerous-looking voids and caverns that can develop as the sidewalls of a stope scale off and fall down into workings.

The Government Mining Engineer's reports of the years 1903 to 1930 referred many times to the appearance of surface cracks in areas where the ground had been undermined. The writer is of the opinion that these cracks were caused by the rock mass settling northwards and downwards: the strata rotated, as it were, about a fulcrum, the fulcrum being the edge demarcating the mined from the unmined reefs, and, as mining progressed deeper, so did the fulcrum, leading to successive cracks on surface. This point is well illustrated by Fig. 4. The writer assumes that the surface positions portrayed are reasonably accurate, and that, as mining moved down

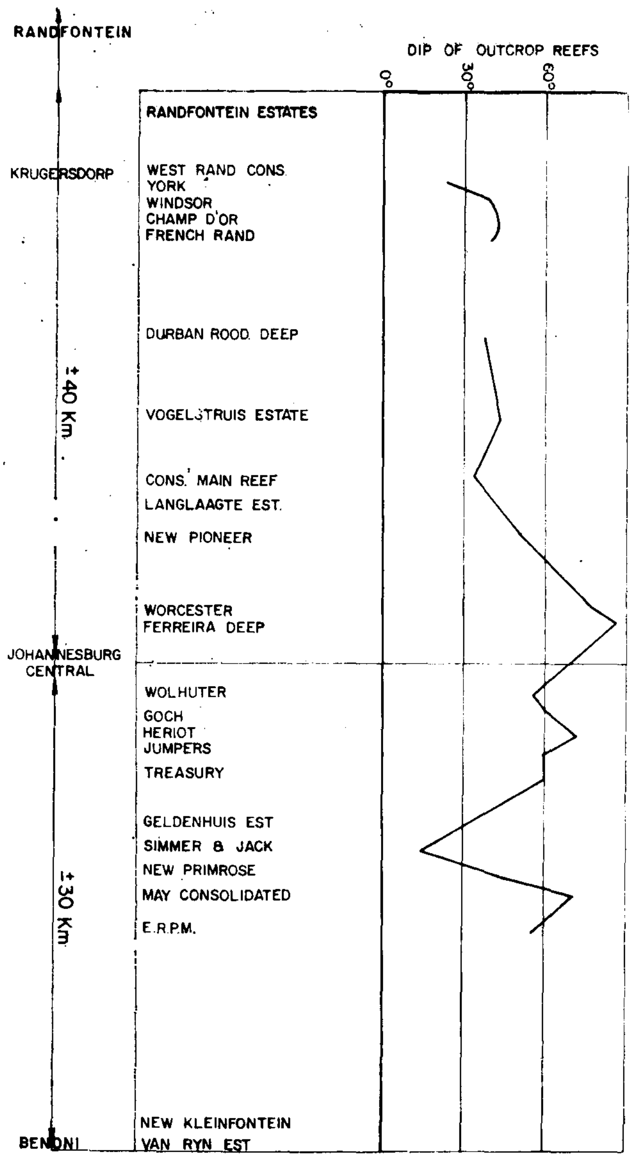


Fig. 17—Location of mines for which cracks were recorded in the annual reports of Government Mining Engineer from 1903 to 1927 (see Table II); also shown are the variations in the dip of the reefs

dip, cracks began to appear on surface in the order shown by cracks 1, 2, 3, 4, and 5, i.e., they were related to the underground fulcrum.

The occurrence of cracks on surface, then, was very much a feature of the pre-1920 mining era, when gold mining on the central Witwatersrand was largely done at shallow depths. Very few of these cracks can be seen today, for they have long since been filled in with rubble and soil. However, a fairly recent example of this type of fracture occurred at the Rietfontein Consolidated Mine. Fig. 19 is a photograph showing a portion of one of the cracks that developed over the northern edge of the pillars depicted in Fig. 20; as the ground settled north of the pillar, it bent round the fulcrum at X (Fig. 21) and, by thus stretching the surface, caused the cracks.

Another example of surface cracks is to be found at New Kleinfontein, as shown in Fig. 22. In this case, however, numerous reefs with a large combined stoping width had been mined, and the closure towards the worked-out reefs was so great that it caused the large tension crack shown.

It is pertinent to ask why, with mining depths of more than 244 m, surface cracking is a rare phenomenon. The writer advances two main reasons: firstly, that the dips of the reefs flatten with depth; and, secondly, that the pattern or sequence of mining has changed.

Decreasing Dip of the Reefs. Fig. 23 shows sections through the reefs at four mines, and Table IV shows the dips at surface and at 244 m respectively.

These changes in dip affect the direction of strata settlement: at the greater depth, the horizontal component of the stress in the rock is far less than near surface, and the strata tend to move down rather than northwards, i.e., the tension stresses at surface are less, and hence the non-occurrence of cracks.

Pattern or Sequence of Mining. Stoping from surface usually advances down dip on a wide front. Examples are shown in Figs. 2, 4, and 6. This sequence of stoping produces a strike fulcrum, and, as the ground settles northwards, tension cracks appear on surface. At greater depths, however, mining from vertical shafts becomes more common, and a typical sequence of mining would be that shown in Fig. 24. Cross-cuts north and south from the shaft and haulages east and west made it possible for stoping to be started on all sides of the shaft; hence a 'fulcrum' situation does not develop, and the tendency for cracks to form on surface is minimized.

Subsidence and Fracture of Strata Immediately Above Stoped-out Reefs

The South Reef and the Main Reef Leader, with widths of approximately 1 m and 1½ m respectively, were the first two reefs to be mined extensively on the central Witwatersrand. The development that preceded stoping followed a straightforward pattern, namely, reef drives at successively greater depths, connected by raises some 100 to 200 m apart. A version of this early type of development in a flat reef is shown in Fig. 25a, the reef drives being about 50 m apart.

Stoping started from the raises, and, as mining progressed both east and west from each raise, supports were installed; once the stoping span exceeded, say, 30 m, the hangingwall strata would sag and settle on the supports, but this settlement would not initially have extended to surface. The phenomenon was mainly that of separation of strata along bedding planes and the formation of a dome of disturbed or fractured rock above the stoped-out area. Fig. 25b shows an 'idealized' plan and section through the stopes when the mined-out span between the stope faces had reached, say, 50 m. Particularly to be noted is the newly formed fracture zone or dome in the hangingwall of each stope. As mining progressed, the ore between the raises was completely mined out and the extent of hangingwall fracture then became that shown in Fig. 25c. The depth of fracture depends largely on the dip of the reefs: for a near-vertical reef, the depth of fracture into the sidewalls would be small because gravity plays very little part in inducing fracture; as the dip decreases, the effect of gravity becomes more pronounced and the 'fracture zone' above the stope increases. The actual depth of fracture at the shallow depths being

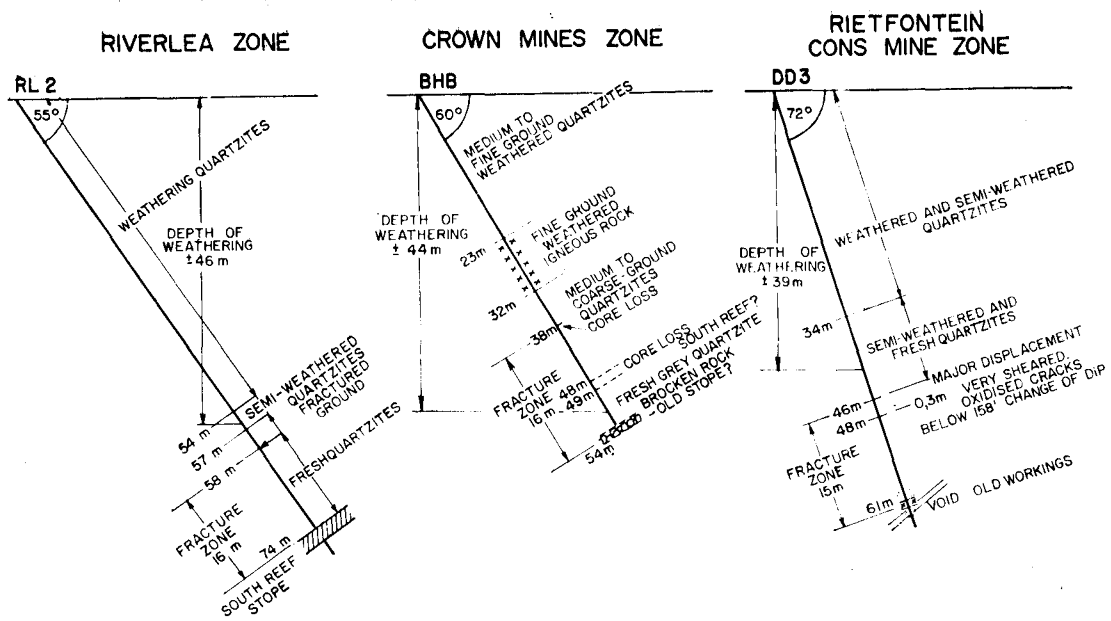


Fig. 18—The logs of boreholes drilled to determine the nature of the strata overlying the stopes, the depth of weathering, and the extent of the fracture zone

TABLE III

DRILL HOLES IN THE CENTRAL WITWATERSRAND

Site	Borehole* no.	(a) Vert. depth to S.R. m	(b) Depth of Weathering m	Compressive strength			Remarks
				Depth of sample m	lb/in²	kPa	
Area N and N.W. of Riverlea township	RL1 RL2 RL3	55 61 54	49 46 54	No. samples taken			Weathered quartzites
Old Mayfair Mine, N. of Crown Mines	BHB BHC	43 58	47 55	27 43 37 55	3800 4800 3200 8500	26000 33000 22000 59000	Weathered quartzites
Ferreira parking ground	DBH3	23	57	No. samples taken			Weathered quartzites
2 erven adjoining Hall St near Westgate Stn	D1 D2	21 (Reef not intersected)	37 35	18 24 37 55	5000 11000 29000 27000	34000 76000 200000 186000	Weathered quartzites Grey, unweathered quartzites
Rietfontein Cons. Mines				34	10200	70000	
Portion 15	DD1	76	18	63	5400	37000	
				32	20900	144000	
	DD2		30	62	9600	66000	
				37	4800	33000	Quartzites
	DD3	59	36	67	16700	115000	
				33	4800	33000	
Portion 402	DD4	88	38	68	5500	38000	
				30	14400	99000	
	DD5	72	26	58	3200	22000	

*Except for DBH3, the drilling of the boreholes was supervised by Dr A. Cluver; DBH3 was logged by Mr C. W. Duke, a geologist attached to the Rand Mines Group.

Fig. 19—A surface crack caused by the subsidence of strata north of the pillars shown in Fig. 20, Rietfontein Consolidated

TABLE IV

APPROXIMATE DIP OF REEFS AT FOUR MINES

Mine	At outcrop	At 244 m
Crown Mines	50°	30°
Village Main Reef	80°	30°
Village Main Reef	85°	30°
Wolhuter	50°	25°

considered is not great, as Table V shows.

Further evidence of the limited extent of the fracture zone was obtained from two sewer tunnels that the City Council completed recently. These are about 25 to 30 m below surface and traverse the outcrops in the Fordsburg Dip area. Their positions are shown in Fig. 26. The first tunnel, marked X–Y, was driven northwards and passed through the mined-out South Reef and Main Reef Leader stopes. The shift-boss in charge of the tunnel reported on the condition of the hangingwall strata as follows:

> Over the last 6 months, at your request, I have made a close study of the tunnel side-walls and hangingwall for any indication whatsoever of any movement due to the under-stoping.

TABLE V

DEPTHS OF FRACTURE ABOVE THE STOPE (IN METRES) AS SHOWN BY BOREHOLE CORES

Croesus Mine			Mayfair Mine	Rietfontein Consolidated Mine			
RL1	RL2	RL3	Dbh2	DD1	DD3	DD4	DD5
23	14	1	11	9	Not detectable	13	Not detectable

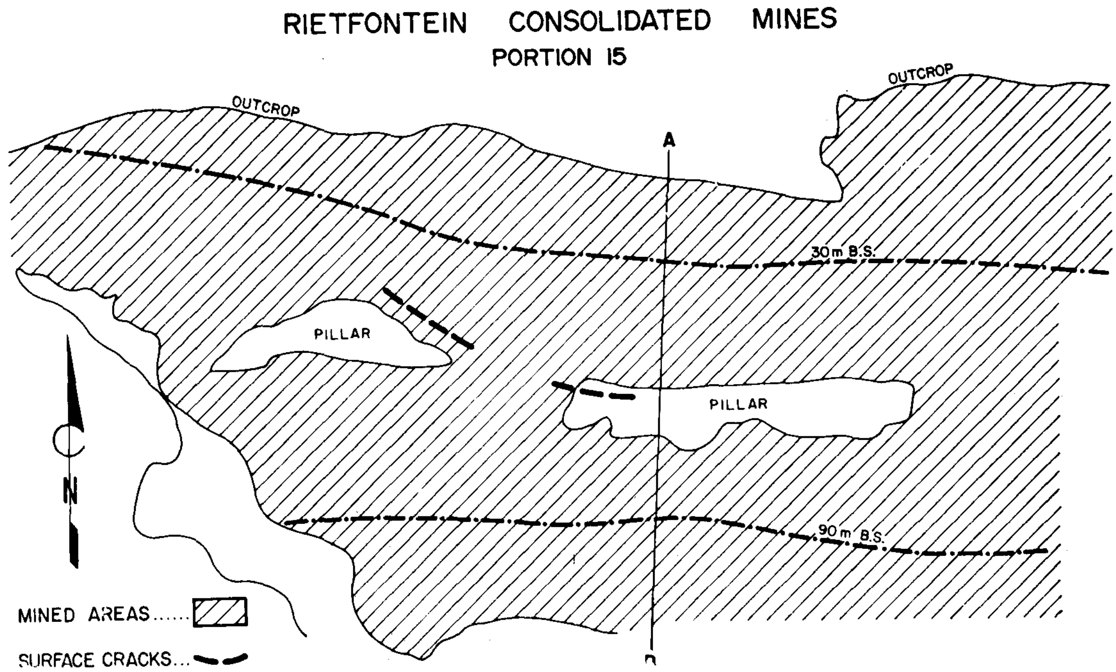


Fig. 20—Plan of Portion 15 of the underground workings, showing the surface cracks that developed on the northern edge of the pillars, Rietfontein Consolidated

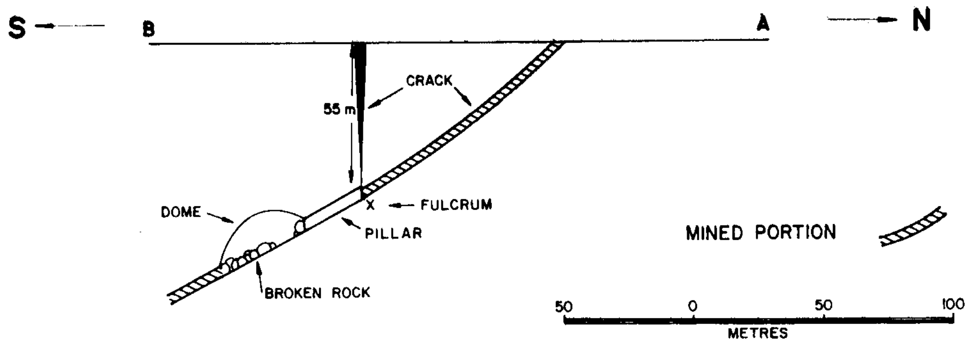


Fig. 21—Section through A–B of Fig. 20, showing a surface crack in relation to a pillar

Fig. 22—Surface crack resulting from the mining of a number of superimposed reefs, New Kleinfontein

> I have not noticed any opening [crack] in the strata through which the tunnel has passed. There has been no indication at all that there was mined-out ground below the tunnel. [Signed] H. Elsmere, 28.7.77.

The second tunnel, driven eastwards from point X and through the fault at point Z, converged on the South Reef workings, and, before crossing the fault, it reached a point only 2 m in the hangingwall of the South Reef. This 350 m length of tunnel, like the first, showed no signs of fracture – on the face of it, convincing evidence that, when closure took place, the movement of the hangingwall strata was *en bloc*.(The only supports installed were where the tunnel traversed two dykes.)

Fracture Due to Geological Discontinuities

Three examples are given below to show how faults or dykes can play a role in causing serious fracture or rupture of the surface

Rand Leases. In the early 1940s, a section of ground north of No. 6 shaft, Rand Leases, showed signs of differential movement, which continued for several years and led to the step shown in Fig. 27. Even though the depth of mining was some 200 m, the management of Rand Leases was perturbed by this fracture, and in 1947 a series of beacons was established on each side of the fracture line to monitor any further subsidence that might occur. Monitoring of the beacons during the period 1947 to 1953 gave the results shown in Table VI. Of interest is the fact that, once mining had ceased, the rate of subsidence slowed down; by 1953, for all practical purposes, the surface was at rest. The fracture did not take the form of an opening due, for example, to tension, but was rather the sliding down of rock strata along a plane of weakness. A study of the mine plan showed a fault running parallel to the direction of the line of fracture, and the inference is that, as the reef north of the dyke was being mined, the overlying strata slid down the dyke plane and left the pronounced step on surface. This is the only example of a 'step fracture' known to the writer, for surface fractures, apart from sinkholes, usually take the form of open tension cracks.

Village Main Reef. The reefs outcropping in what is now the central part of Johannesburg were mined more than fifty years ago. In 1951, a substantial subsidence of

TABLE VI

MONITORING SURVEY AT RAND LEASES, 1947 TO 1953

Beacon no.*	Elevation 6.6.47 ft	Elevation 7.8.50 ft	Difference 1947-1950		Elevation 15.1.53 ft	Difference 1950-1953	
			ft	mm		ft	mm
1N	–416–43	–416–45	—0,02	6	–416–45	—0,00	0
2N	–415–24	–415–30	—0,06	18	–415–31	—0,01	–3
3N	–413–23	–413–31	–0,08	24	–413–32	–0,01	–3
5N	–407–64	–407–67	–0,03	9	–407–68	–0,01	–3
1S	–417–08	–417–09	–0,01	3	–417–08	+0,01	+3
2S	–415–93	–415–93	0	0	–414–92	+0,01	+3
3S	–414–16	–414–17	–0,01	+3	–414–13	+0,04	+12
5S	–408–45	–408–43	+0,02	+6	–408–44	–0,01	–3

*N—north of fracture S—south of fracture

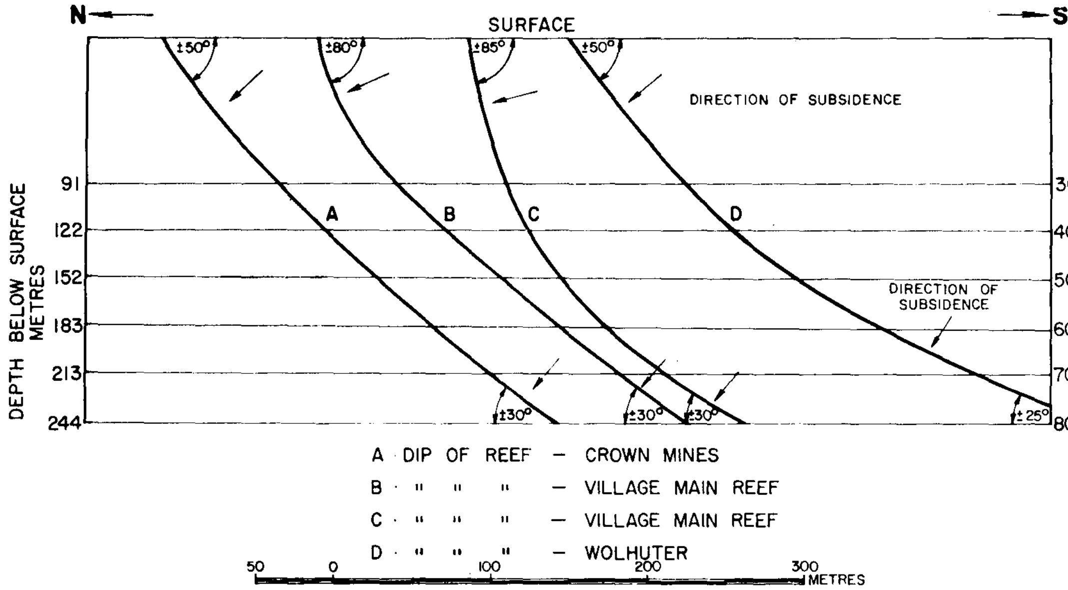


Fig. 23—Change in dip of the reefs of the Central Witwatersrand with depth

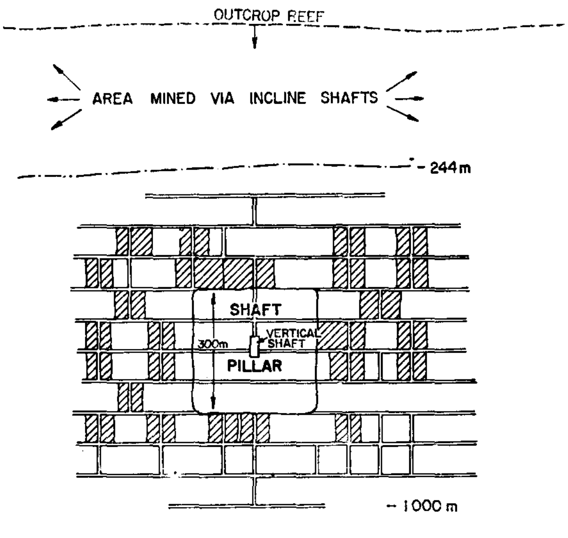


Fig. 24—Plan of the typical stoping pattern before longwall stoping became normal practice for a deep-level mine

the surface occurred on the South Reef horizon between Sauer and Simmonds Streets, and Haak's Garage was in danger of being seriously damaged. Remedial work was undertaken by Village Main Reef, and in a report dated 24th February, 1954, Mr D. A. Immelman gave a full account of the measures taken to ensure the stability of the surface and the reasons why, in his judgment, abnormal settlement had occurred.

Fig. 28 is a cross-section at the site of the subsidence. The dykes shown in the sketch lie in the footwall of the mined-out South Reef, which has a dip of some 80°. The tendency would be for the wedge to slide down the slippery slope of the soft, weathered dyke, and this is in fact what happened. In the words of Mr Immelman, the

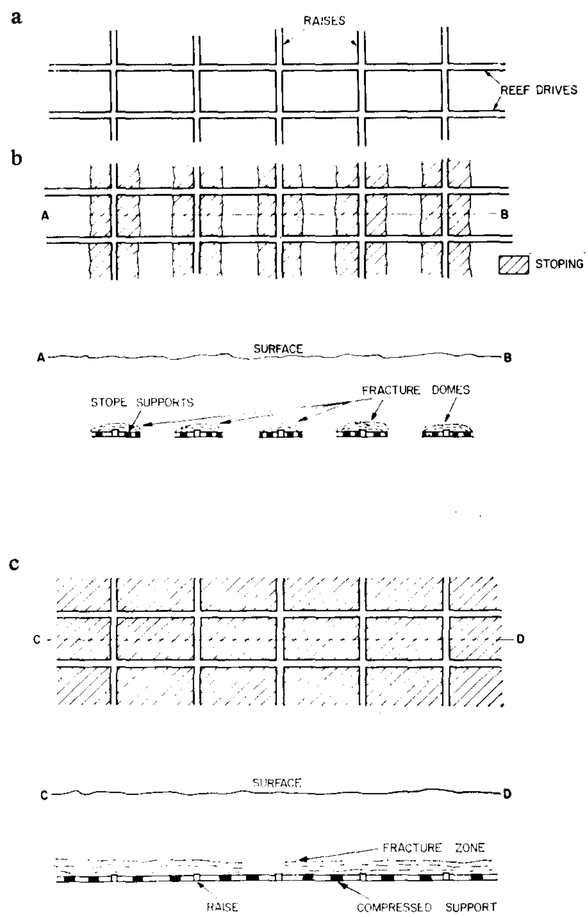


Fig. 25—Plans showing how, with the progress of stoping, a fracture zone develops above the stopes

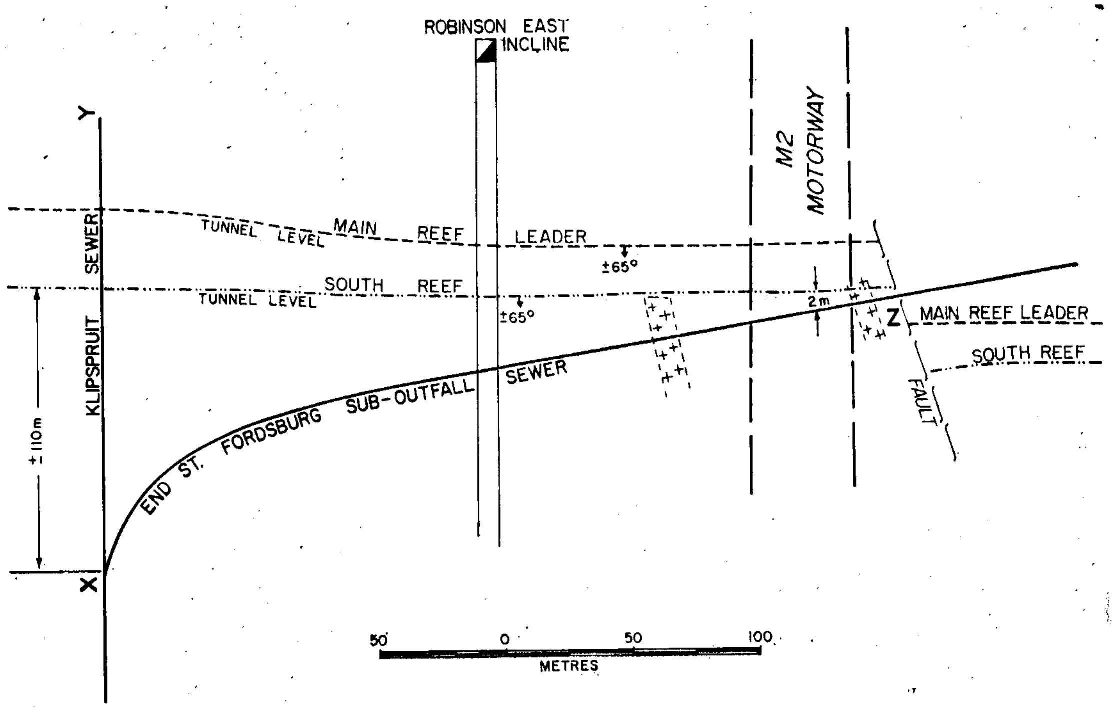


Fig. 26—Location of sewer tunnels in relation to the underground workings

Fig. 27—'Step' fracture with a length of about 100 m and a 'step' of about 0,4 m, Rand Leases

'wedge of ground between the stope and the dyke fell away into the stope, probably as the result of ground water seeping along the dyke and lubricating the plane of contact'. The writer agrees with this appraisal.

Nourse Mines. The following are extracts from an unpublished thesis by Dr A. B. A. Brink.

In May 1942 the ground surface over an area of nearly half a hectare immediately south of the South Reef outcrop workings near the eastern boundary of Nourse Mines, suddenly subsided by an amount of 2 metres.

. . .

It will be seen [from Fig. 29] that the dyke dipped steeply towards the workings. The subsidence was thus clearly due to a simple slope failure under the weight of the largely unsupported hangingwall wedge over the entire depth of the very steeply-inclined stope.

That collapses of this nature could cause considerable damage is clear from Fig. 30: three houses in the area had, in fact, to be demolished. Similar occurrences, and for the same reasons, have occurred elsewhere on the Witwatersrand, and indicate that caution is necessary in the assess-

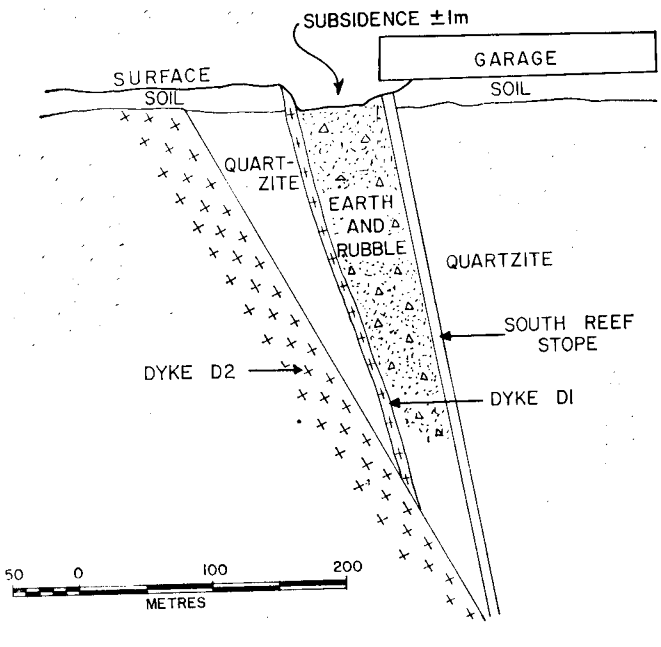


Fig. 28—The subsidence of a wedge of ground between a dyke in the footwall and a worked-out stope, City Central

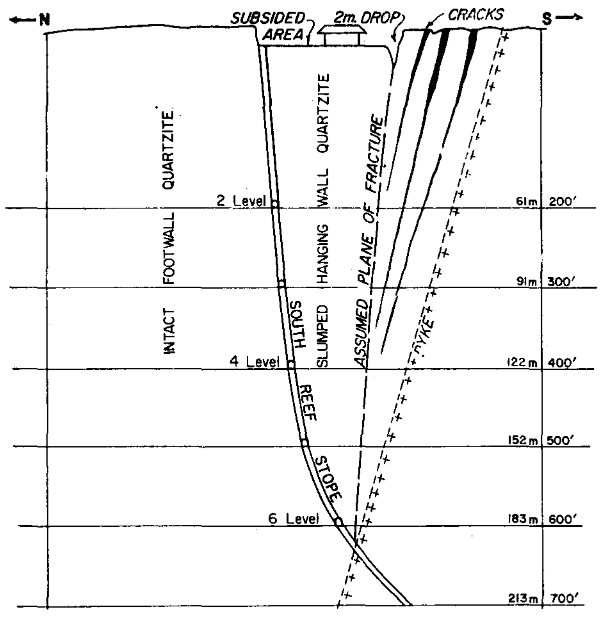


Fig. 29—The subsidence of a wedge of ground between a dyke in the hangingwall and a worked-out stope, Nourse Mines

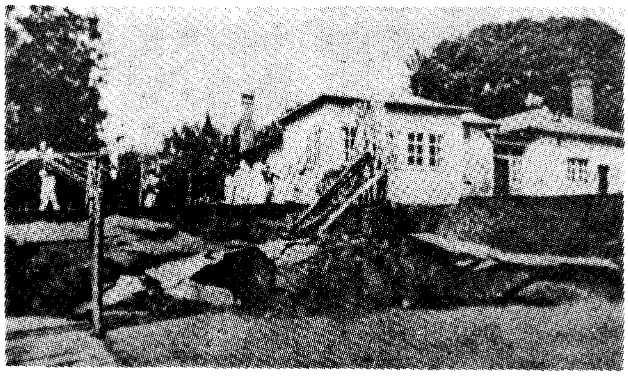


Fig. 30—Surface rupture caused by the collapse of the wedge of ground depicted in Fig. 29, Nourse Mines

ment of the stability of an area where the outcrops are close to a fault or dyke. The geology and geometry of any particular site are of prime importance.

Surface Subsidence and Fracture Summarized

The subsidence and fracture of ground undermined at shallow depths can be summarized as follows.

(i) Subsidence invariably occurs where reefs have been fully mined-out. The amount and rate of subsidence depend on the dip of the reef, stoping widths, the support in the stopes, and the presence or otherwise of faults or dykes.

(ii) Fracture commonly occurs in this situation (though in varying degree), depending again on the dip of the reef, stoping widths, the support in the stopes, and the presence or otherwise of faults or dykes. The types of fracture discussed are illustrated in Fig. 31. The undermined ground is divided into three zones: the first, Z1, is that of the actual outcrop areas; the second, Z2, is the zone extending from the point where the depth of undermining is 50 m to the point where the depth of undermining is 244 m; the third, zone Z3, is the ground undermined at a depth greater than 244 m.

Zone Z1, for the reasons given previously, should always be investigated thoroughly before decisions are made on surface usage. Zone Z2, important because of potential surface usage, may contain both near-vertical tension cracks and 'separation of strata' fracturing of the immediate hanging of the stope. However, once mining has ceased for, say, twenty years, this zone is relatively free from stress, and the mass of solid rock is inert, at rest, and presents no danger to persons using the surface. Zone Z3 is ground that the Department of Mines considers so stable that building restrictions do not apply.

Subsidence and Fracture from 1947 to 1980

As the evidence shows, ground undermined at shallow depths subsides and fractures, and no one could therefore claim that the restrictions imposed by the Government Mining Engineer some thirty years ago were unreasonable. However, there does not appear to have been a systematic examination of the position once the ground had settled. To remedy this matter, the writer helped to persuade interested parties to establish and monitor the subsidence of survey beacons above mined-out ground and thus determine whether or not the surface had become stable. There now exist from the Croesus Mine on the west to Riet Consolidated on the east no fewer than 9 separate zones where survey programmes have been carried out. The location of some of these zones, which are listed in Table VII, is shown in Fig. 32.

Zone A – Riverlea (Fig. 32)

One of the most severe building strictures placed on the use of undermined ground is that no dwelling houses may be erected where the depth of undermining is less than 800 ft (244 m). This had until recently prevented the extension of the present township of Riverlea northwards – an extension pressingly needed to cope with the ever-growing population.

In December 1972, the City Engineer asked the writer to obtain information on which the stability of this northerly ground could be judged. The programme embarked upon consisted in the drilling of boreholes and the taking of subsidence measurements. It was hoped that the results, when presented to the Department of Mines, would show the ground to be so stable that, if dwelling houses were to be erected over the bulk of the area, there would be no danger to life or property.

The assignment was completed towards the end of 1973. In addition to the drilling and survey programme, a full study was made of the main factors that influence fracture and subsidence: the extent of mining; the width and dip of the reefs; the presence or otherwise of pillars, faults, and dykes; the support in the mined-out areas; and the length of time since mining had ceased. The City Engineer's staff did the survey work according to the following procedure.

(a) *Beacon Construction.* A hole 30 cm in diameter and 75 cm deep was filled with concrete, and a brass stud 10 cm long was placed on top of the concrete.

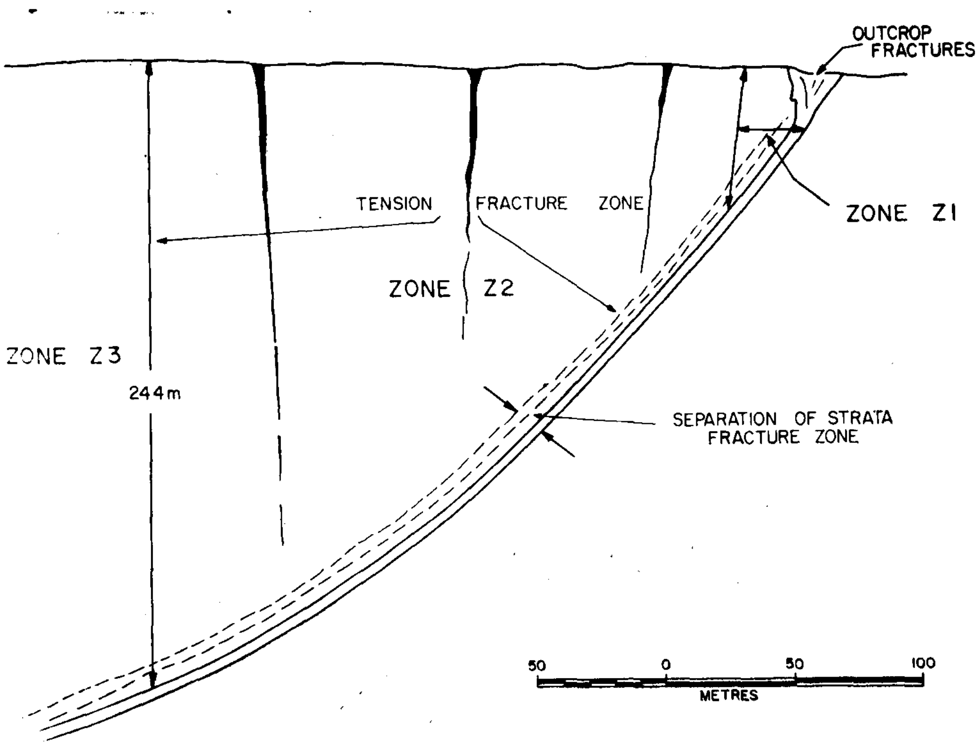


Fig. 31—Diagrammatic sketch showing the different types of hangingwall fracture

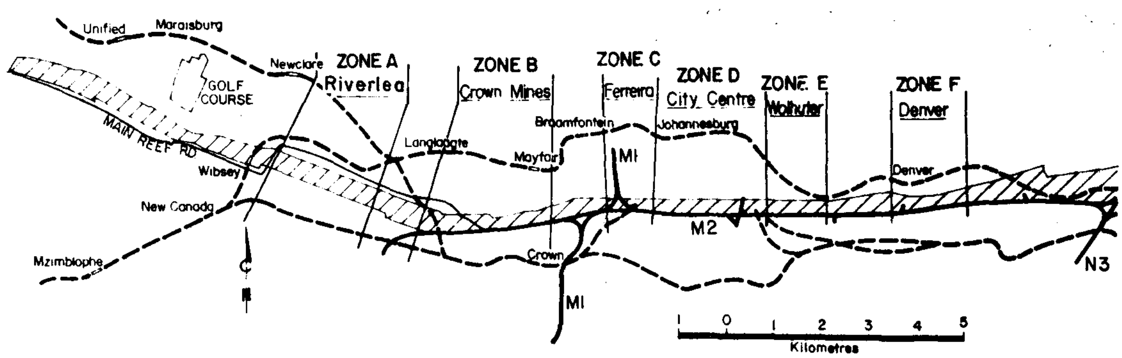


Fig. 32—Location of zones A to F, where subsidence surveys have been conducted

(b) *Instruments and Staves.* Use was made of Zeiss No. 2 level metric staves at intervals of 1 cm.

(c) *Accuracy of Survey.* Accuracy of the tertiary order i.e., $\pm 0{,}010$ m was aimed at. Any difference from this order was ignored, since it would not indicate movement.

(d) *Traverse Lines.* Six lines with four beacons per line were established across the area; one beacon was placed north of the outcrop, and the remaining three at approximately 150 m intervals.

The positions of the beacons in relation to the underground workings and the proposed extension area to Riverlea township are shown in Fig. 33. From 1959 to 1967, the Croesus Mine had done reclamation work in the upper areas of the property, which had previously been mined extensively on both the Main Reef Leader and the South Reef horizons. The extent of mining can be judged from Fig. 34, which shows a portion of the mine near the Croesus shaft; also to be seen on Fig. 34 are the positions of traverse lines C3, C4, and C5.

The results of these monitoring surveys are shown in Figs. 35 and 36. It will be noted that, except for beacons 1 and 2 of traverse line C1, no changes in elevation occurred outside the limits of accuracy postulated in the monitoring project. The reason for the unusual behaviour of these two beacons is probably that, as the base beacon north of the outcrop is on the edge of a main road, it was depressed by passing traffic.

It is contended that these results show that the whole of the area north and north-west of the present Riverlea township is stable. Attention should be given to the fact that the ground is stable whatever the depth of undermining; thus, the movements of beacons C2-2, C3-2, C4-2, and C6-2, where the depths of undermining are less than

TABLE VII

SURVEY PROGRAMMES CONDUCTED IN THE CENTRAL WITWATERSRAND

Date survey started	Zones where beacons were established and monitored		No. of beacons installed	Agency doing the Survey work
	Zone	Name		
January 1973	A	Riverlea (Croesus area)	24	City Council Survey staff
August 1955	B	Crown Mines including Mayfair	60	RMP Survey Staff
March 1969	C	Ferreira	7	Chamber of Mines R A C
November 1971	D	City Centre	84	City Council Survey Staff
April 1974	E	Wolhuter	26	Prof. I. B. Watt, University of Witwatersrand
March 1969	F	Denver–Nourse	10	Chamber of Mines
March 1976	G	Stanhope	16	Primrose Mine Survey Staff
October 1977	H	Geldenhuis	34	Prof. I. B. Watt, University of Witwatersrand
October 1972	I	Rietfontein Consolidated	59	Mr R. A. Greenwood (Land surveyor)

RIVERLEA

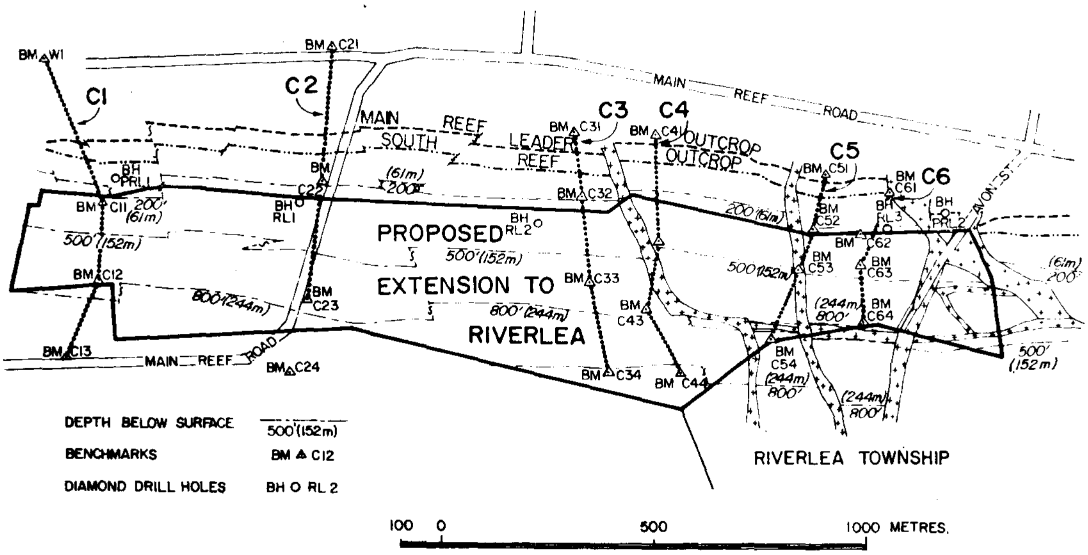


Fig. 33—Plan of zone A, showing traverse lines C1 to C6 in relation to the proposed extension to Riverlea township

80 m, are almost identical to those of beacons C2-3, C3-3, C4-3, and C6-3, where the depths of undermining are greater than 80 m (Figs. 34 and 35). These facts seem to justify the writer's contention that building restrictions for areas with undermined depths of more than, say, 50 m need be no more limiting than for areas that are undermined more deeply.

Apart from the survey results shown in Figs. 34, and 35, there is evidence from the Croesus area to show that the surface has come to rest. In 1940 a beacon was established north of the outcrops between traverse lines C2 and C3, and a second beacon was put in south-west of the first, in a position where the depth of undermining is 305 m. A precision survey by the Trigonometrical Survey Office showed that, after 28 years of large-scale reclamation mining, from 1940 to 1968, the undermined beacon had subsided 1,0 ft (300 mm). This beacon was remeasured in 1972, with the results shown in Table VIII.

It will be noted that, between 1968 and 1972, the surface did not move; it had reached a state of equilibrium. Here, then, is a large area of some 300 acres, which has settled down; the undermined strata have compressed the supports, as well as the fracture zone above the stopes, and have come to rest. The presence of dykes in the area (Fig. 34) has not altered the 'stability' picture, for, where there is no movement, there cannot be differential movement.

It is concluded, then, that there would be no danger to

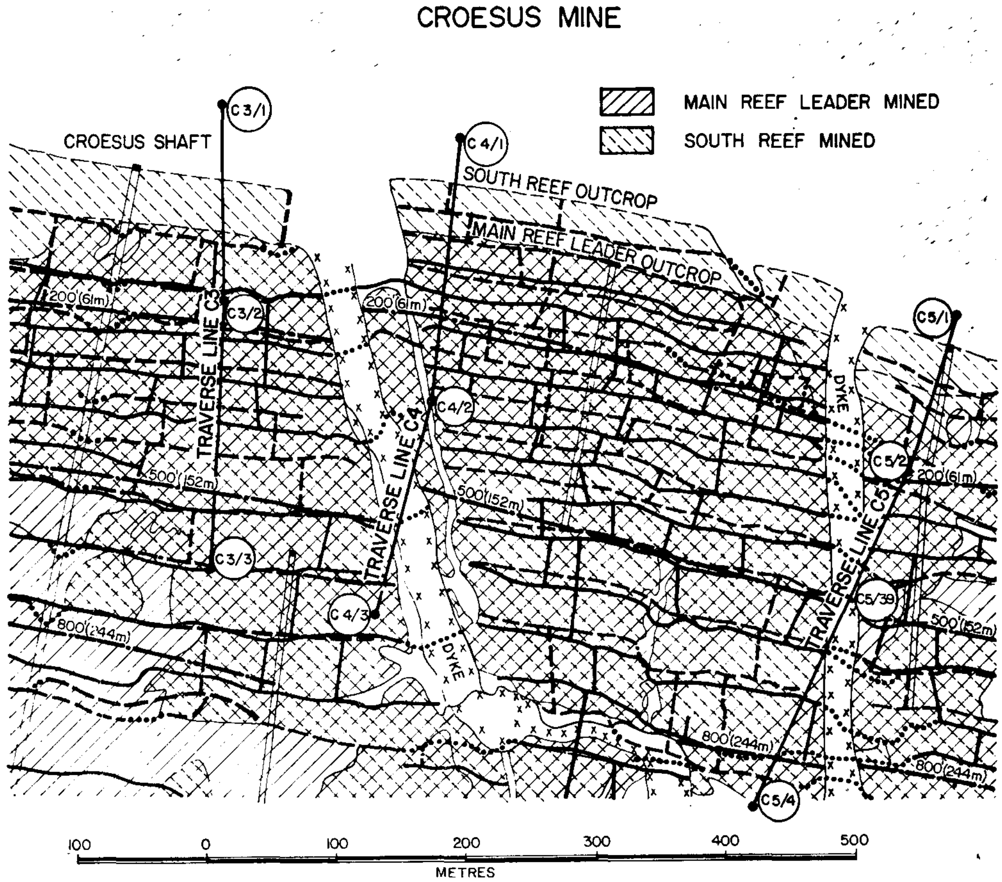


Fig. 34—Plan of a portion of the underground workings of the Croesus Mine (zone A), showing the extent of stoping and the position of the traverse lines C3, C4, and C5

TABLE VIII

SUBSIDENCE OF UNDERMINED BEACON, CROESUS AREA

Date	Elevation of beacon north of outcrop	Elevation of beacon south of outcrop	Total subsidence	
			Feet	mm
1940	+5552,69	+5558,03	0	0
1968	+5552,69	+5557,03	1,0	300
1972	+5552,69	+5557,03	1,0	300

life if a township were established in the area, provided houses were not built on or adjacent to the reef outcrops. This conclusion stems not only from the above surveys, but also from a study of the history of subsidences on the central Rand during the past 75 years; during this period, the casualty rate from subsidences or surface cracks (excluding outcrop areas and dolomitic sinkholes) has, from the available evidence, been zero. The risk of damage to buildings, should these be erected in the area, is also virtually zero for the simple reason that the hangingwall strata have reached a state of rest.

The results obtained from the survey and drilling work carried out north and north-west of Riverlea township convinced the Department of Mines that the current restrictions on the development of townships where depths of undermining are less than 244 m could in this case be modified; in the event, permission was granted for houses to be built where mining depths exceeded 150 m. This concession was far too conservative in the writer's view, but it was valuable economically and socially. The facts speak for themselves: between the depths of 150 and 244 m, there is sufficient room on surface to build some 680 houses; if the area overlying the undermined depths between 50 and 150 m were to be included (and this would have the writer's full support), a further 430 houses could be built. It can readily be imagined what extra costs would have fallen on the community if the building restrictions had not been amended. Had this Riverlea area not become available, the 680 houses would probably have been sited at Ennerdale Township, some 35 km south of Johannesburg. The extra costs referred to would include capital expenditure on the pro-

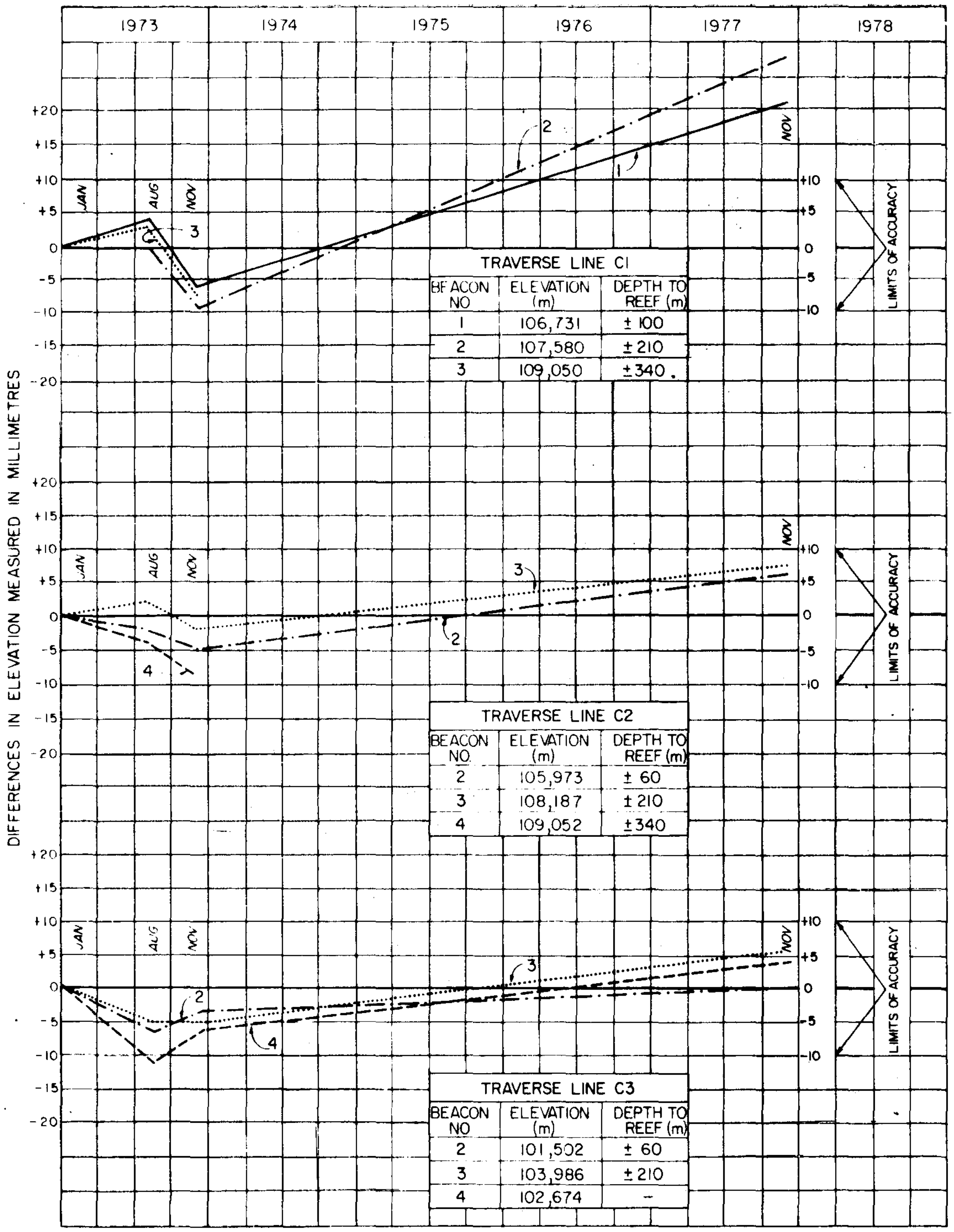
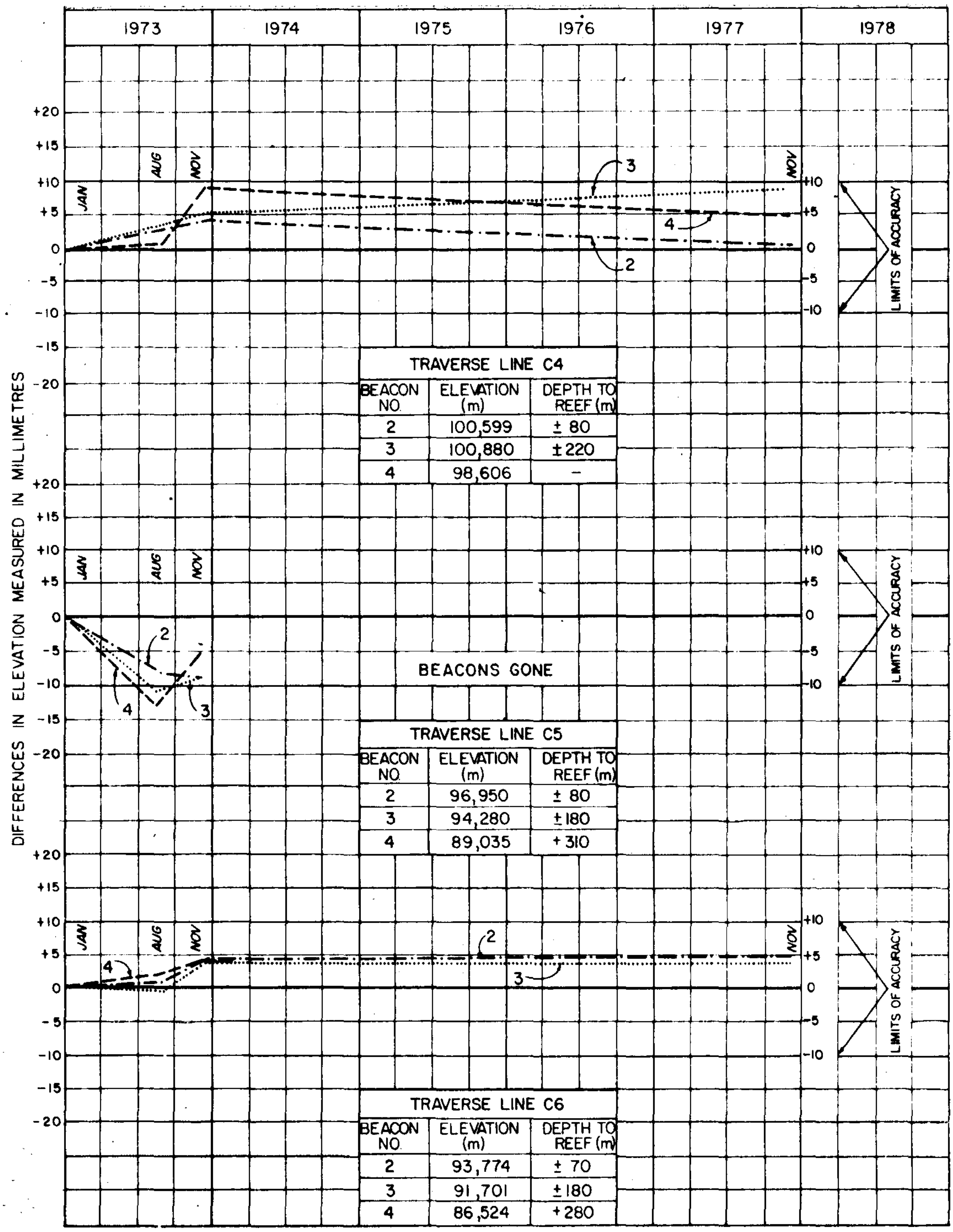


Fig. 35—Graphs showing elevations of beacons along traverse lines CI to C3, Riverlea North, zone A (assumed elevation of beacons north of the outcrop 100 m)



TRAVERSE LINE C4		
BEACON NO.	ELEVATION (m)	DEPTH TO REEF (m)
2	100,599	± 80
3	100,880	± 220
4	98,606	–

TRAVERSE LINE C5		
BEACON NO.	ELEVATION (m)	DEPTH TO REEF (m)
2	96,950	± 80
3	94,280	± 180
4	89,035	+ 310

TRAVERSE LINE C6		
BEACON NO.	ELEVATION (m)	DEPTH TO REEF (m)
2	93,774	± 70
3	91,701	± 180
4	86,524	+ 280

Fig. 36—Graphs showing elevations of beacons along traverse lines C4 to C6, Riverlea North, zone A (assumed elevation of beacons north of the outcrop 100 m)

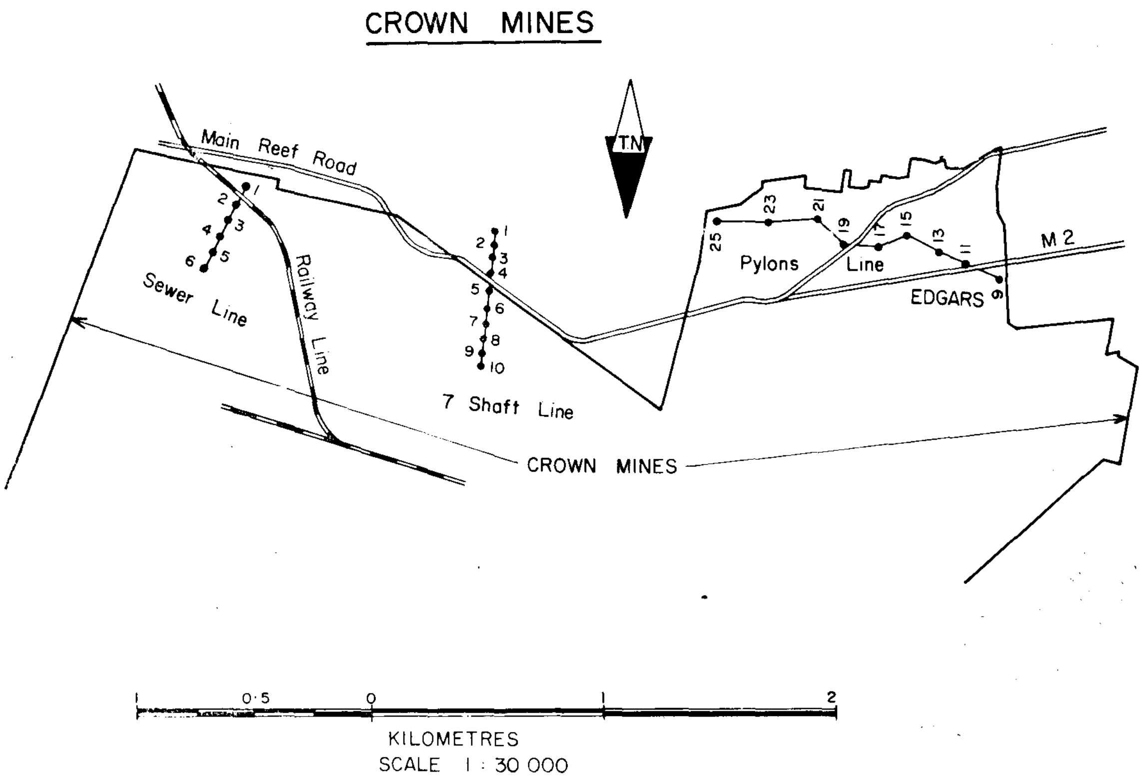


Fig. 37—Plan showing the location of three traverse lines in Crown Mines zone B

vision of infrastructure, and, *inter alia*, excessive fuel costs in the transportation of workers to the industries where they were employed. Apart from cost considerations, however, is the fact that proximity to work adds greatly to the quality of life.

Zone B – Crown Mines (Fig. 32)

There does not appear to be any area on the central Witwatersrand where subsidences have been recorded systematically over a longer period than at Crown Mines. For many years, beacons have been monitored along five traverse lines. The three selected for comment in this paper, which are shown in Fig. 37, are as follows:

(a) along a main sewer line traversing the outcrops,
(b) along a north–south line through No. 7 shaft, and
(c) along a line of pylons.

The Sewer Traverse Line. The beacons were established on manholes as shown in Fig. 38. The survey results for the past ten years are depicted in Fig. 39. Beacons MH2 and MH3 are situated on a large dyke and, as is to be expected, show no downward movement; beacons MH4 and MH5, on the other hand, have been subsiding very slowly, the total subsidence over twelve years being 45 mm for MH4, and 39 mm for MH5. What is remarkable about the two subsidences is their 'parallelism', indicating strongly that the rock mass is subsiding *en bloc*, i.e., the settlement is not differential. The measurements over the past two years suggest that further downward movement will be negligible.

The No. 7 Shaft Traverse Line. The position of this traverse line in relation to the underground workings is shown in Fig. 40. The subsidences of beacons 2, 3, 7, and 10 as depicted in Fig. 41 show clearly a decreased rate of

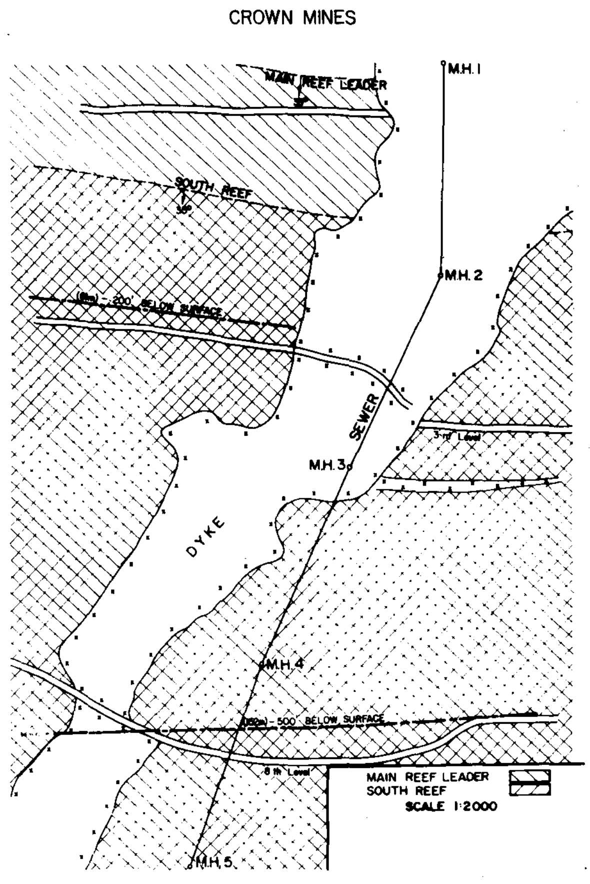


Fig. 38—The sewer traverse line, Crown Mines (zone B)

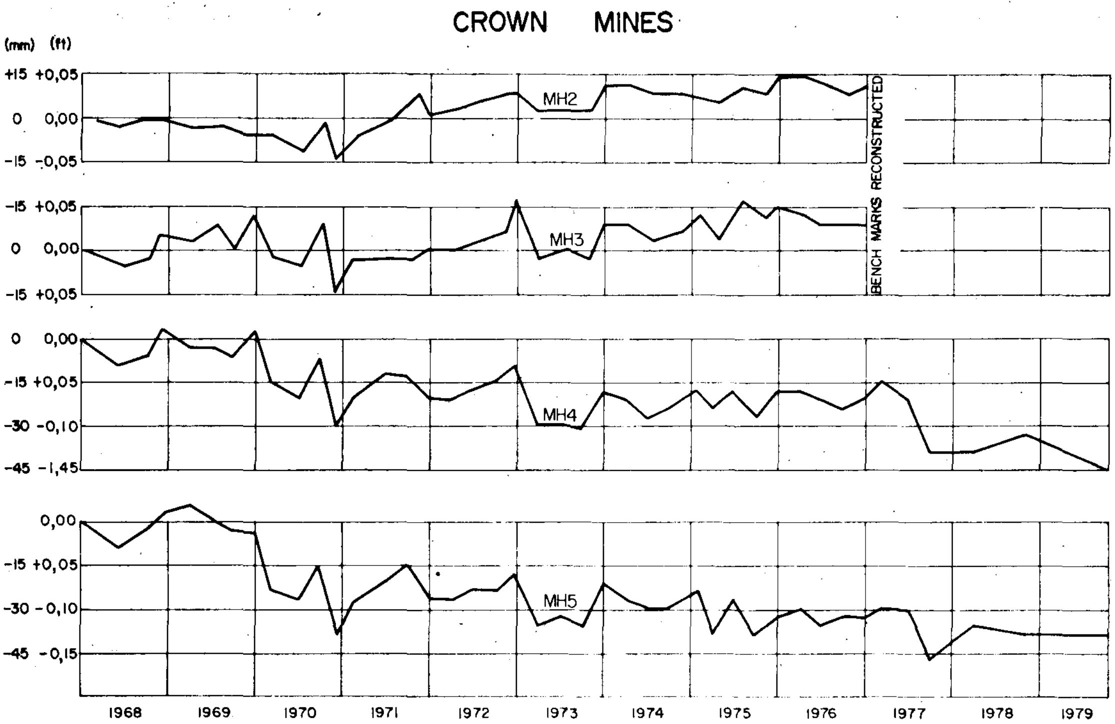


Fig. 39—Subsidences of beacons along the sewer traverse line, Crown Mines (zone B)

subsidence with time until a state of zero subsidence was reached. The reason for the comparatively large subsidence of beacons 7 and 10 was the removal of No. 7 shaft pillar (Fig. 40). This renewed mining caused the surface to settle over a wide area, extending, for example, to beacons 2 and 3, which were an average distance of 300 m from the shaft. All four beacons indicated *en bloc* settlement, although beacons 7 and 10 subsided some 24 mm more than 2 and 3. This 'tilting' southwards of the surface, amounting to no more than 8 mm per 100 m, is so slight that, had there been buildings on the undermined area, they would not have been affected by the settling of the surface.

The Pylons Traverse Line. This traverse line has a very long history. Monitoring started more than thirty years ago and has produced subsidence records of great value. The positions of the pylons are shown in Fig. 37, and Fig. 42, which is a section through No. 2 shaft, shows some of these pylons in relation to the underground workings. Subsidence over the years has been substantial, pylon 15 having subsided no less than 1,5 m. Fig. 43 gives a revealing picture of how the surface sank during the period 1948 to 1979. The subsidences of the pylons shown all tell the same story: once mining ceases, the rate of settlement slows down until the rock mass overlying the stopes comes to rest. A point to be stressed again is that all the beacons have stopped subsiding: pylon 21, where the depth of undermining is 66 m, is as much at rest as pylon 15, where the depth of undermining is 195 m. The building of houses on ground adjoining pylon 21 is judged to be as safe as building on ground near pylon 15; in other words, the depth of undermining is not a criterion of safety, and, as stated earlier, where mining has ceased for twenty years or more, the only suspect areas from the point of view of safety are those adjoining the outcropping reefs.

Zone C – Ferreira

Two of the most informative and valuable of the levelling projects of the past ten years have been those carried out by the Chamber of Mines research team at the Ferreira Estate parking ground and at Denver. The surveys were conducted over a period of ten years with great accuracy, and the subsidence figures show clearly the amount and rate of settlement. The following are extracts from a report prepared by the Chamber's Mr K. I. Oravecz in July 1972:

Precise Levelling

Networks of benchmarks were laid out for the measurement of vertical displacements in the outcrop areas of Ferreira Estate and City Deep (Denver Zone).

Two types of stations formed the networks. The 'borehole' benchmarks were established by concreting 50 mm diameter steel pipes on 141 mm diam. vertical boreholes that were drilled 0.9 m into solid bedrock or to a maximim depth of 4.5 m. The measuring marks comprised brass studs brazed to the top of steel pipes. Concrete collars and screw-on covers protected the benchmarks. 'Surface' benchmarks were established by setting brass studs either in existing structures or in blocks of concrete, 0.3 m cube in size and set level with the existing surface. The two types of benchmarks served to separate spurious soil movements from displacements induced by mining.

The design of the 'borehole' beacons is shown in Fig. 44, and their positions in Fig. 45. According to Mr Oravecz's report:

Eight borehole stations were established in this area. Station 1 was set in the footwall approximately 35 m away from the Main Reef outcrop and served as the reference station.

Stations 2 and 3 were in ground undermined by the Main Reef and Main Reef Leader only. Stations 4 to 8 were, in addition, undermined by the South Reef. Station 4 was situated close to a dyke.

The first readings were taken on 20th March, 1969, and

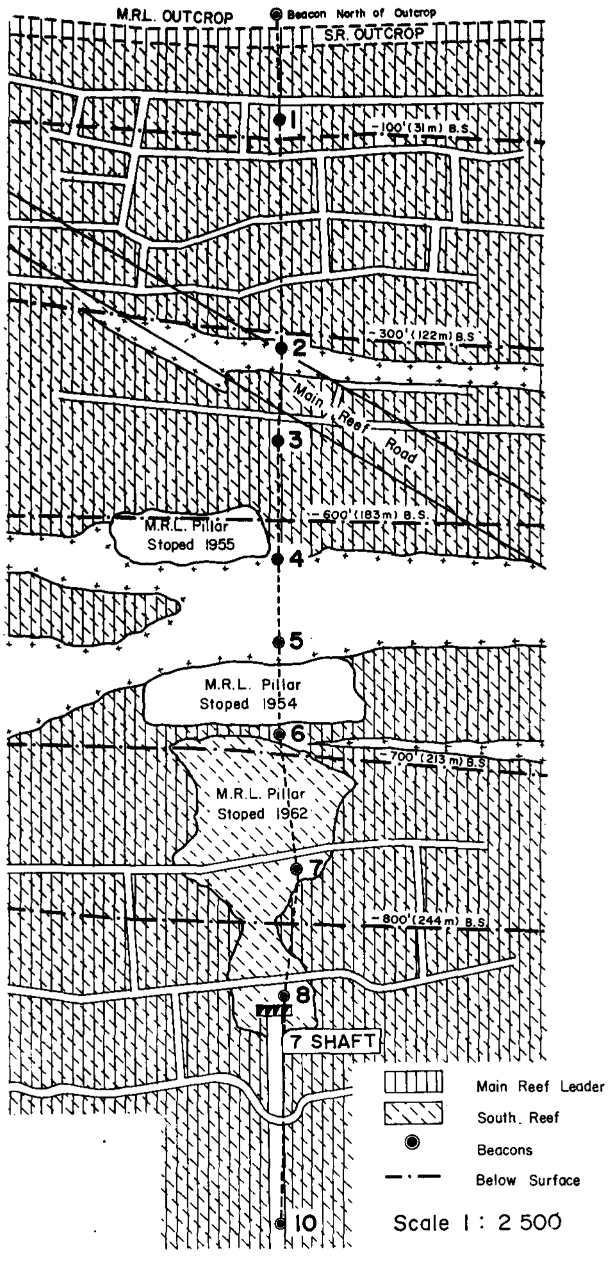


Fig. 40—Location of 7 shaft traverse line in relation to the underground workings, Crown Mines (zone B)

the original and subsequent readings, which are shown graphically in Fig. 46, show the following.

(a) Steady, uniform settlement of the strata. Of interest is the fact that benchmarks 2, 3, and 4 subsided slightly less than benchmarks 5, 6, 7, and 8. The reasons would seem to be that 2 and 3 lie above only the Main Reef and Main Reef Leader stopes, whereas 5, 6, 7, and 8 lie above the South Reef as well. The lesser subsidence of 4 is probably due to its proximity to a dyke;

(b) *En masse* settlement, i.e., non-differential settlement. The maximum difference in subsidences between 5, 6, 7, and 8 is 3 mm. This type of settlement needs constant emphasis since it is the chief reason why no fears should exist regarding the stability of buildings erected on undermined ground where mining has ceased and where there is an adequate thickness of competent rock. Of significance is the fact that the difference in subsidence between benchmarks 5, 6, and 8, which lie on the strike of the reef, is only 1 mm; benchmark 7, lying well to the south, where the depth of mining is greater, shows most subsidence.

(c) A decrease in the rate of settlement. During the first 6¾ years, the average rate was 0,95 mm per annum, whereas the average rate during the past 3¾ years has been only 0,76 mm per annum.

Reclamation mining in the area ceased about twenty years ago, and it is therefore surprising that the ground has continued to subside for so long, even if at an increasingly slower rate.

The conclusion to be drawn is that, because the rate of non-differential settlement is negligibly low, there would be ample justification for allowing buildings of a substantial size (two storeys and more) to be erected on those portions of the site where the depths of mining are more than 50 m. The actual outcrop areas are currently in use for parking, appropriate precautions having been taken to guard against the possible formation of sinkholes.

Zone D – City Central

In November 1971, the Assistant City Engineer of Johannesburg, Mr J. Fulton, convened a meeting of persons interested in subsidence due to mining. The meeting was attended by representatives from the Department of Mines, the Chamber of Mines, the C S I R, the South African Railways, the University of the Witwatersrand, the South African Institute of Civil Engineers, and the City Engineer's Department, as well as several persons in their private capacities.

The problems connected with strictures on undermined ground were discussed at some length, and it was agreed that research work was highly desirable. In the event, towards the end of 1971, the City Engineer's Department established five survey lines across the outcrops, and another eleven in January 1973. These survey lines, situated between the western and eastern municipal boundaries of Johannesburg, have lengths varying from about 460 to 1000 m. There are usually four beacons on each line, the north beacon being beyond the outcropping reefs. The City Engineer's survey staff used a Sunray engineering level and other precise instruments for the levelling work, and regular measurements have been taken at intervals since 1972.

The positions of twelve of these lines are shown in Fig. 47. As subsidence results from the areas to the west of Johannesburg are discussed elsewhere in this paper, only the central group of survey lines (West, Von, End, Kazerne, and Benrose) is considered here.

Fig. 48 gives the results of the surveys and, in general, shows that movements have been minimal to zero, i.e. less than 1 cm, with a few exceptions. One exception is point 2 on the line West; inspection of this beacon, which is on a pavement in West Street, suggests that the beacon subsided because it was depressed by heavy equipment in use in the area. The second exception is point 3 of the line End. The surveyor who was responsible for the measuring states that the unusually large movement was

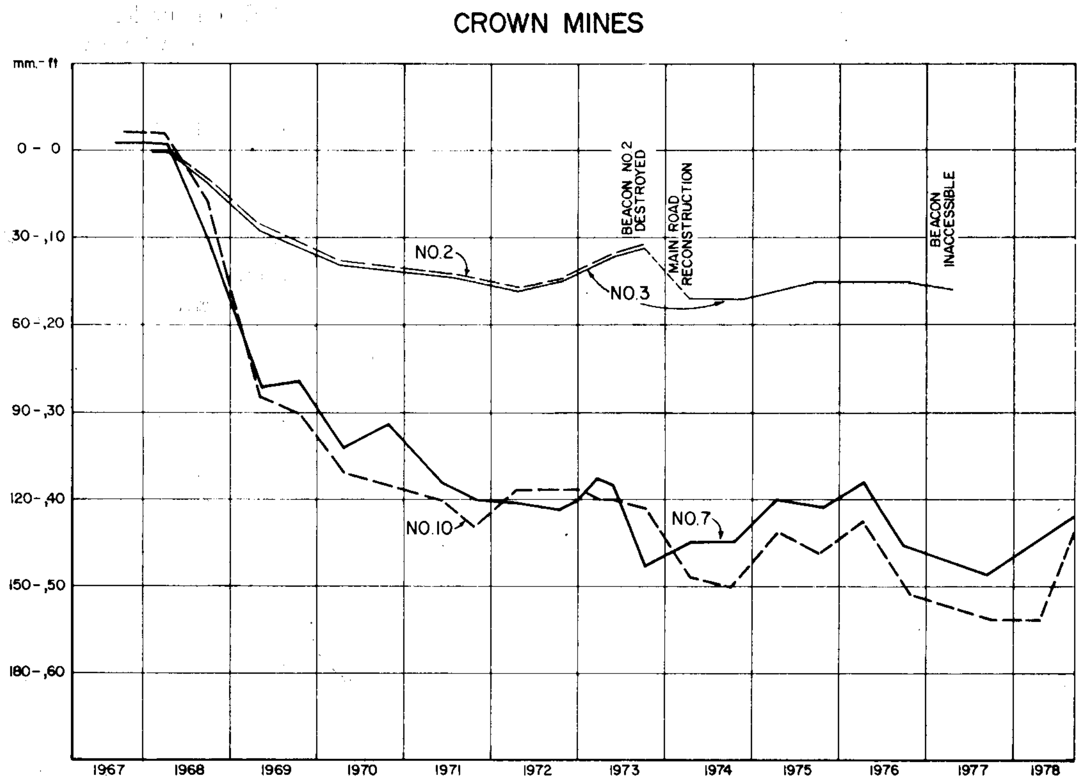


Fig. 41—Subsidences of beacons along the 7 shaft traverse line Crown Mines (zone B)

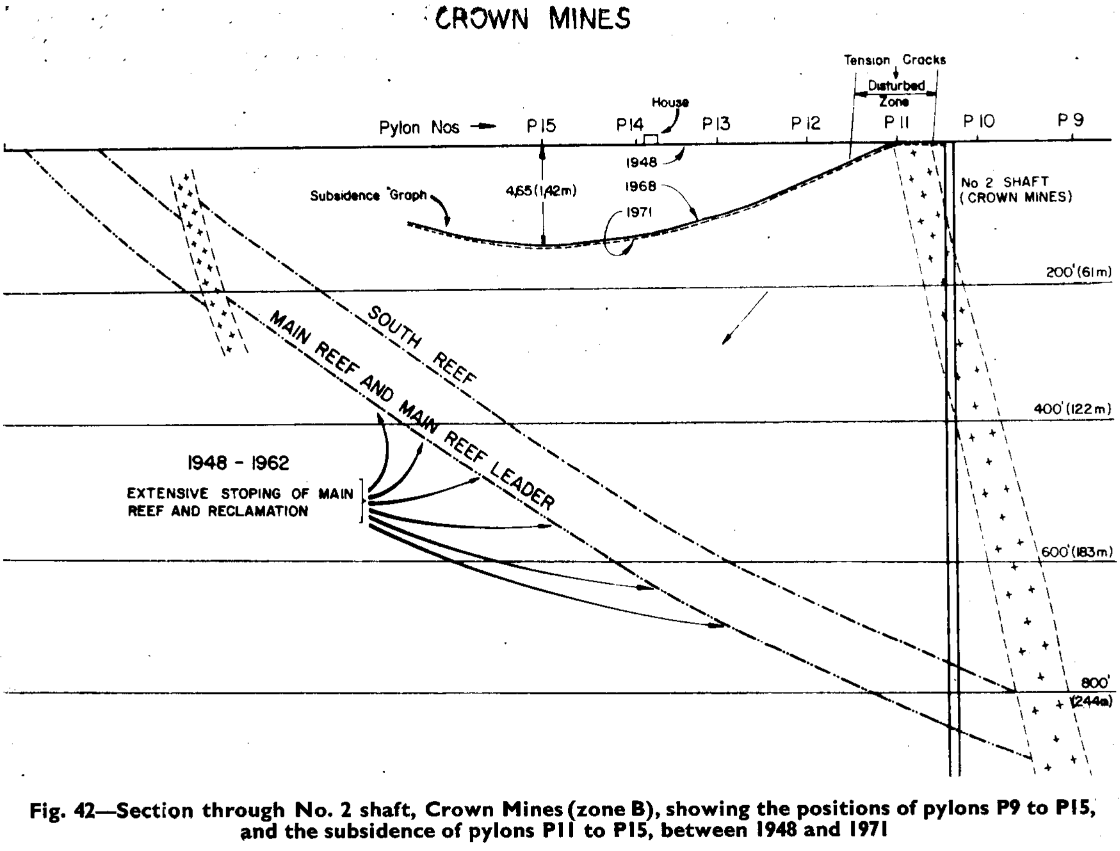


Fig. 42—Section through No. 2 shaft, Crown Mines (zone B), showing the positions of pylons P9 to P15, and the subsidence of pylons P11 to P15, between 1948 and 1971

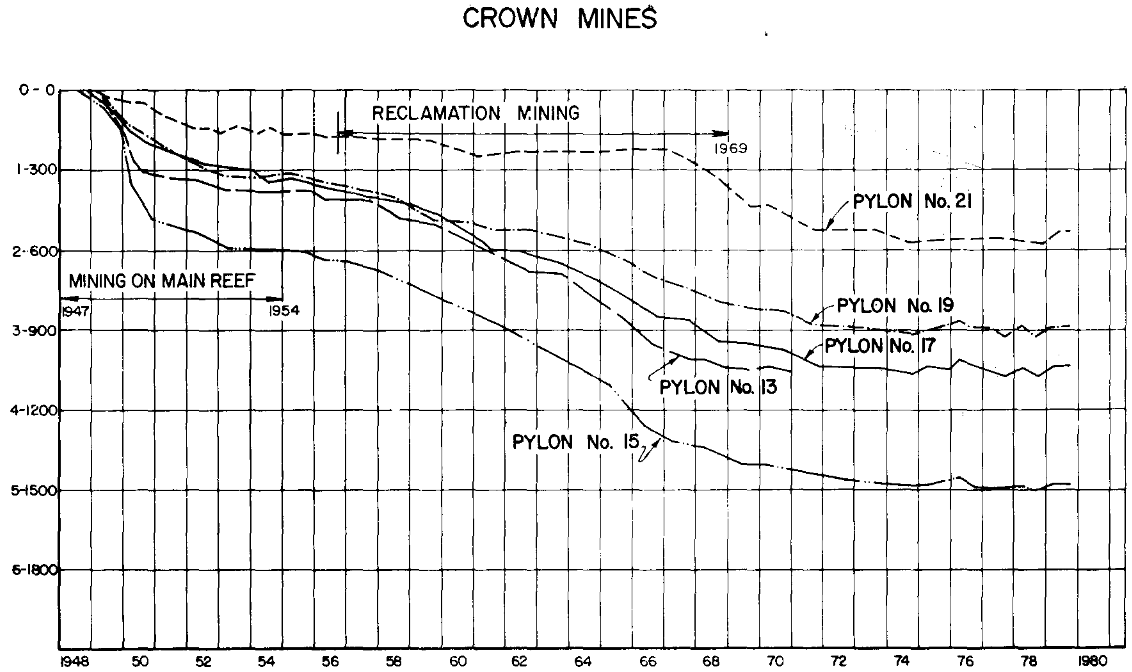


Fig. 43—Subsidence of beacons on the pylons traverse line, Crown Mines (zone B)

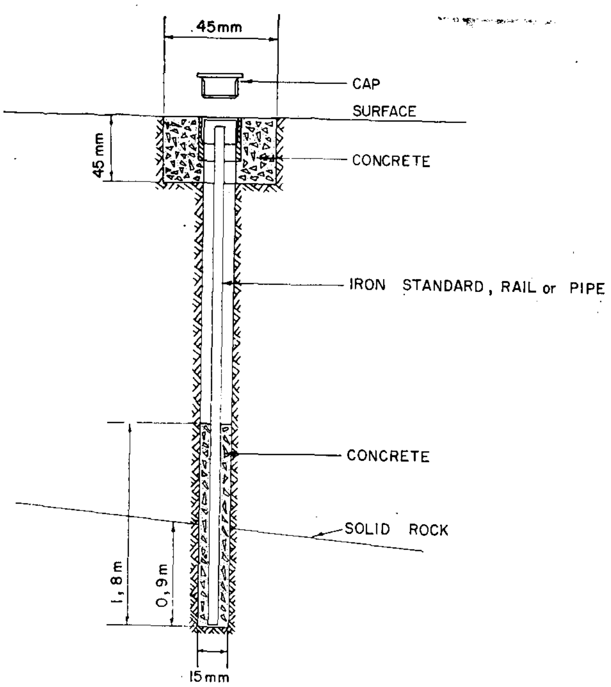


Fig. 44—Design of beacons in Ferreira parking ground (zone C) Depth of hole 0,9 m solid rock or 4,5 m max. Diameter 15 mm

due to 'shifting sand' – probably compaction of the soil.

Apart from these traverse lines, precise levelling on the east–west(M2) motorway structures shows that no significant movements occurred over a period of five years: points on Bridge 84 have moved a maximum of 24 mm, on Bridge 81 a maximum of 38 mm, and on Bridge 6 a maximum of 5 mm. The writer attributes most of the movement on Bridges 84 and 81 to soil compression rather than to movement of the main rock mass. One reason for this opinion is that the outcropping reefs in the centre of Johannesburg dip very steeply, i.e., from 80° to 86°, thus lessening the tendency of the hangingwall to downward movement; and a second is that the position of the bridges is above the soft, weathered Crown–Ferreira dyke.

Zone E – Wolhuter

In July 1972, Wolhuter Estates (Pty) Limited approached the Mining Commissioner with a view to having the proposed industrial stands shown in Fig. 49 reserved for township purposes. The Mining Commissioner replied as follows:

> Due to the gold left in situ and the shallow undermining at stoping widths of 3 to 5 metres the establishment of a township on the stands . . . is opposed in the interests of mining, safety and health.

Faced with this reply, a director of the company asked the writer to investigate the underground and surface positions of the area with a view to ascertaining the existence or otherwise of potentially profitable orebodies, and determining the stability of the area. Extensive studies at that time led to the conclusion that exploitation of the remaining ore in the mine would be uneconomic. The sole reason for withholding permission for the establishment of a township thus seemed to rest on the premise that the ground was unsafe.

As shown earlier in this paper, fracture of the surface was commonplace and in some areas settlement was substantial in the pre-1927 era, when a great deal of mining was being done at depths of less than 244 m.

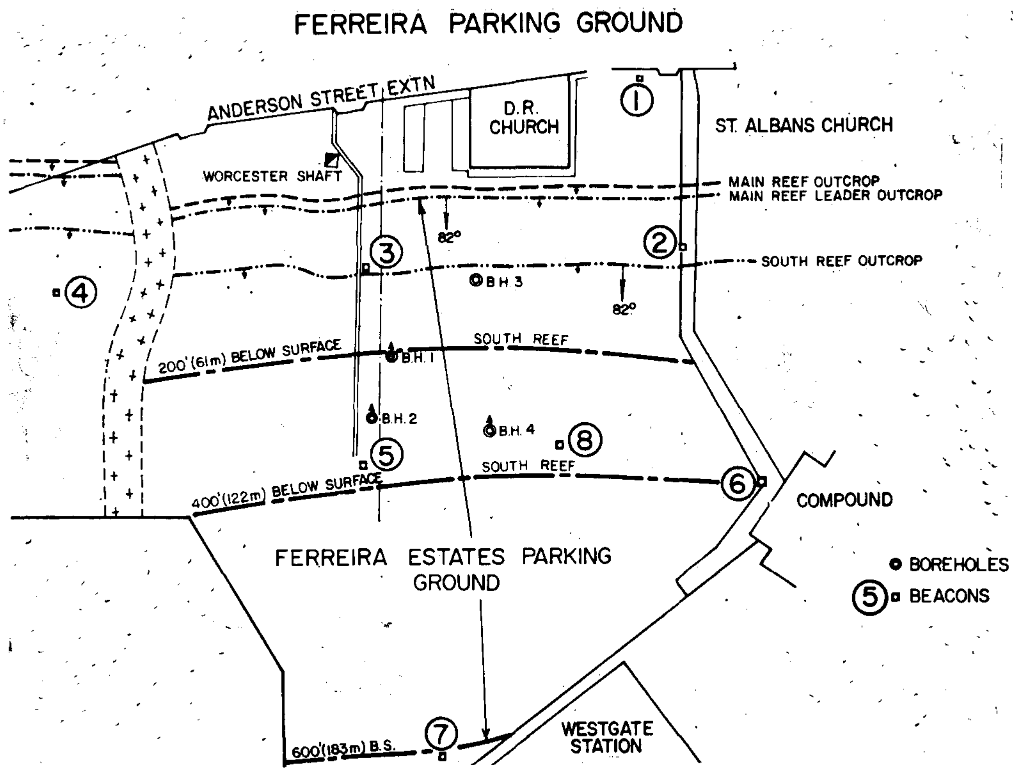


Fig. 45—Positions of beacons in relation to the South Reef andMain Reef Leader outcrops, Ferreira parking ground (zone C)

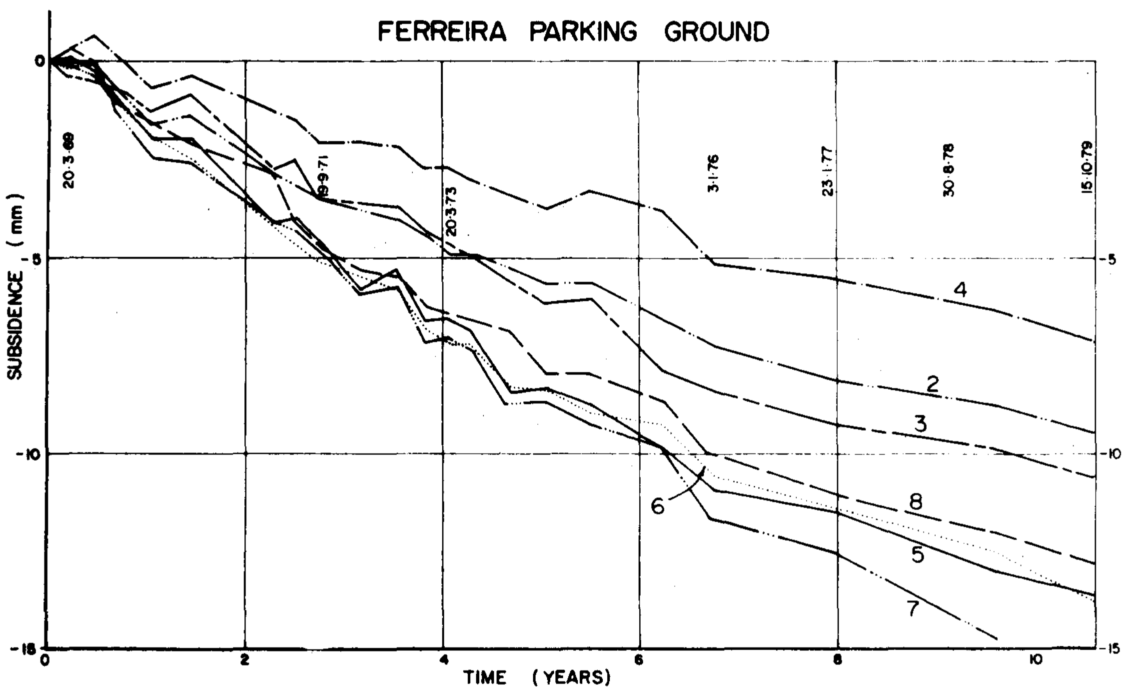


Fig. 46—Graphs showing subsidences of beacons during the period 1969 to 1979, Ferreira parking ground (zone C)

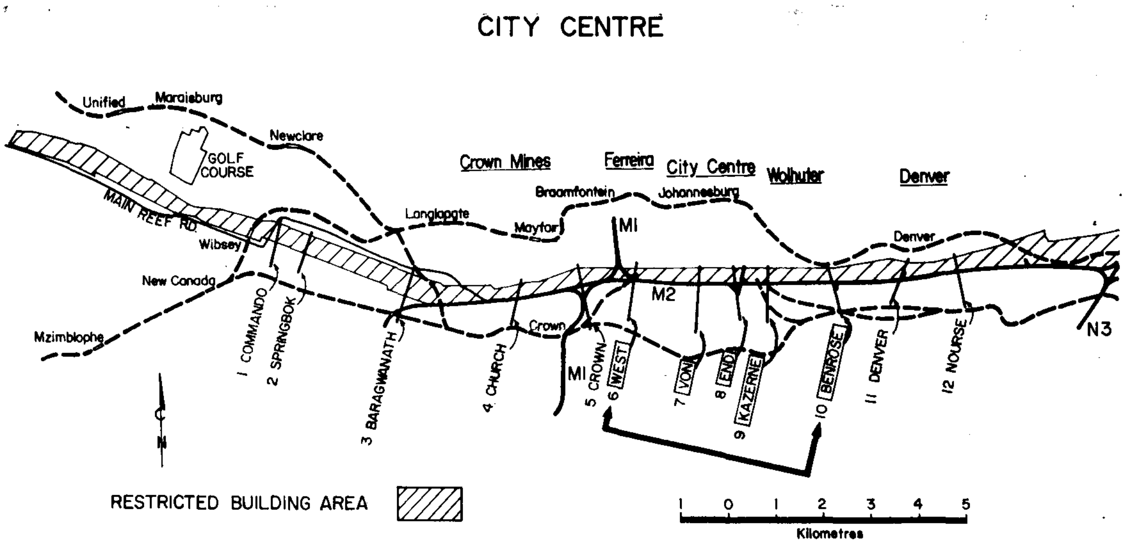


Fig. 47—Positions of the twelve traverse lines established by the City Council, City Centre (zone D)

However, once this near-surface mining had ceased, the ground settled and visible manifestations of movement, such as cracks, came to an end. As mining at the Wolhuter site finished in 1944, it was reasonable to assume, from subsidence records at Crown Mines and elsewhere, that the ground was stable. But, as facts speak more strongly than assumptions, it was decided to install beacons and monitor these to determine whether subsidence had indeed stopped.

Professor I. B. Watt, Professor of Surveying at the University of the Witwatersrand, undertook to do the surveys. To ensure a high degree of accuracy, special beacons(Fig. 50) were inserted in holes deep enough to reach solid rock. The sites of the beacons, fixed in collaboration with the Inspector of Mines, are shown in Fig. 51. The results of the surveys (between April 1974 and February 1976) are given in Table IX.

TABLE IX

SURVEYS IN WOLHUTER, ZONE E

Beacon no.	Approx. depth to South Reef m	Subsidence after 4 months mm	Subsidence after 22 months mm
1	45	0,3	0,3
2	105	0,0	0,9
3	105	0,3	0,3
4	103	0,3	0,4
6	100	0,5	2,0
7	65	0,1	1,2
8	100	0,2	0,5
9	23	0,6	0,6
13	105	0,5	3,0

As with the subsidence data from Crown Mines, Riverlea, and Ferreira, the depth of undermining has little bearing on surface stability. Beacons 2, 3, and 4 straddle a dyke but show no differential movement, for the simple reason, again, that, where there is no movement, there cannot be differential movement.

Professor Watt, in summing up the results of his surveys, made the following statement (March 1976):

> Current measurements reflect remarkable stability in the vicinity of benchmarks 1, 2, 3, 4, 8, and 9, where the observed subsidence is of the order of the accuracy of the measurements themselves. Benchmarks 7 and 11 show downward movements of 1.2 and 3.0 mm with respect to the initial survey. One may therefore conclude that minimal surface subsidence has occurred over the period of the observation.

The depth of undermining of most of the ground comprising this Wolhuter site is greater than 30 m (Fig. 52). The dip of the reefs near surface is 55°, and the distance between the South Reef and Main Reef Leader outcrops is about 20 m. The portions where protective measures might prove necessary are, as usual, the actual outcrop areas, but, as at Ferreira Estates, these outcrop areas, duly protected, would serve admirably for parking.

It can be concluded that, if buildings were erected on this site, they would not be damaged by subsidence provided that no further mining is done in the area. With the present high price of gold, the mine may well be reopened for reclamation mining; in that event, because of the large areas of intact reef in the mine (Fig. 52), renewed subsidence of the surface would certainly occur.

Zone F – Denver–Nourse

Mr K. I. Oravecz, in a report dated 30th July, 1975, summed up the position at Denver as follows:

> The levelling network at this site (consisting of 10 borehole stations with their associated surface stations) comprises two loops; the network is quite extensive and a number of stations have been damaged, resulting in a break in continuity of the observations.
>
> The average rate of subsidence over the full 6½ years of observations amounts to about 0,6 mm per annum, and the calculated average rate over the last 2½ years amounts to less than 0,2 mm per annum. This latter figure is so small that it is considered to be within the error band of observations.

The results from this site, then, confirm those from all the levelling projects considered so far: that, once mining has ceased for, say, twenty years or more, the undermined ground reaches stability and becomes suitable and safe for the erection of buildings.

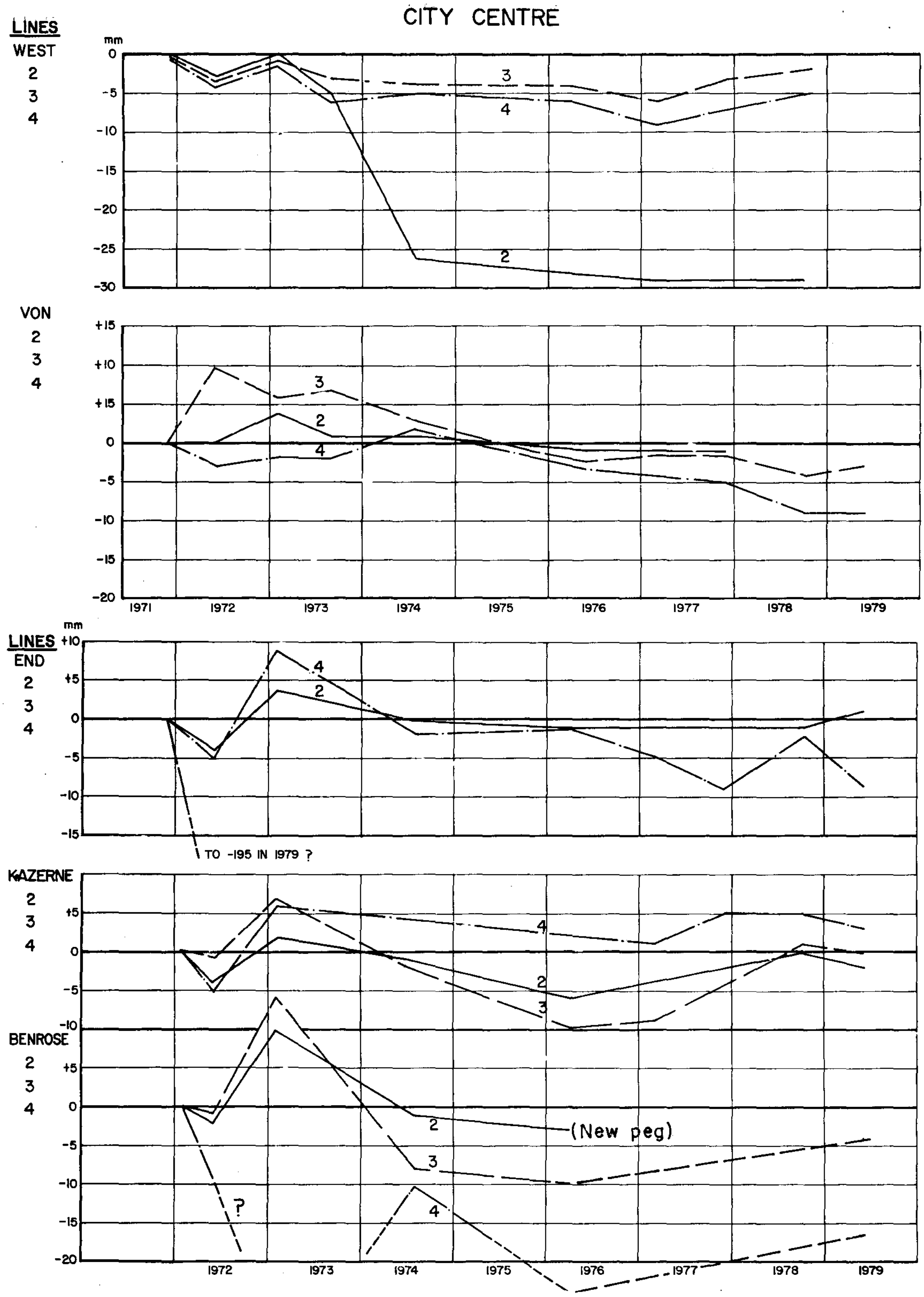


Fig. 48—Subsidences of beacons along five of the traverse lines established in the City Centre (zone D)

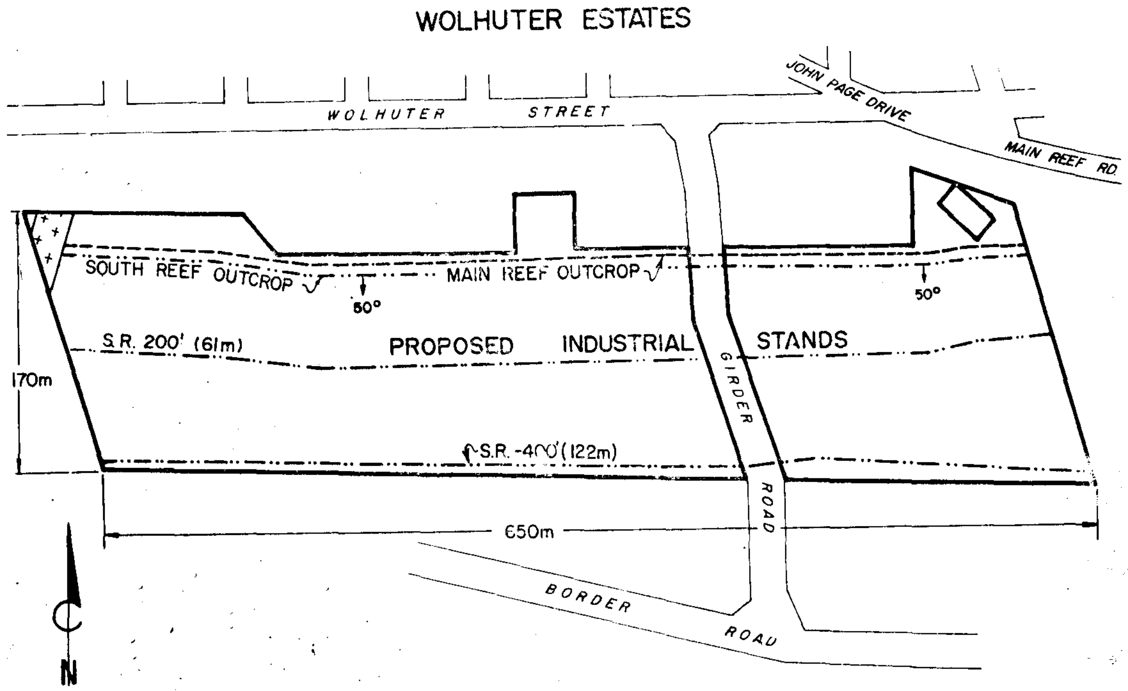


Fig. 49—Plan of proposed industrial stands, Wolhuter (zone E), showing depth of undermining

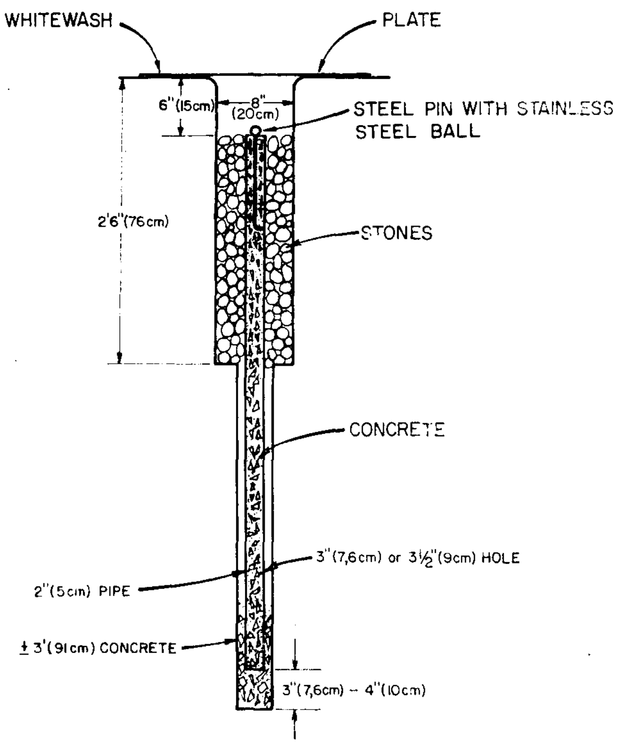


Fig. 50—Design of beacons used at Wolhuter (zone E)

Zone G – Stanhope

At the request of the Department of Mines, the Stanhope Gold Mining Company has been monitoring beacons in a section of the Railway Reserve lying between Cleveland and Geldenhuis Stations. The positions of these beacons are shown in Fig. 53. The reason for the request was that the Mine proposed to reclaim ore under the Main Reef Road and the railway line, and it was considered that this work might affect the surface. The results of these monitoring surveys are shown in the Table X.

It will be noted that, during the first four years of the survey (from March 1975 to January 1979), surface movement was minimal. This was followed by a spell of relatively rapid but non-violent subsidence of all the beacons, showing that a large area had started settling. Before an explanation can be offered for the resumption of surface subsidence, consideration must be given to the physical condition of the hangingwall strata in the area, and the conditions in the mined-out stopes prior to reclamation.

Physical Condition of the Hangingwall Strata. The Government Mining Engineer, in his reports for the years 1905, 1909, 1917, and 1920, refers not only to surface cracks that appeared on the Geldenhuis Estate and Geldenhuis Deep Mines, but also to appreciable subsidences; one subsidence in particular is mentioned as being 350 mm. Inspection of the surface just east of the dyke shown in Fig. 53 confirms that massive subsidence has indeed

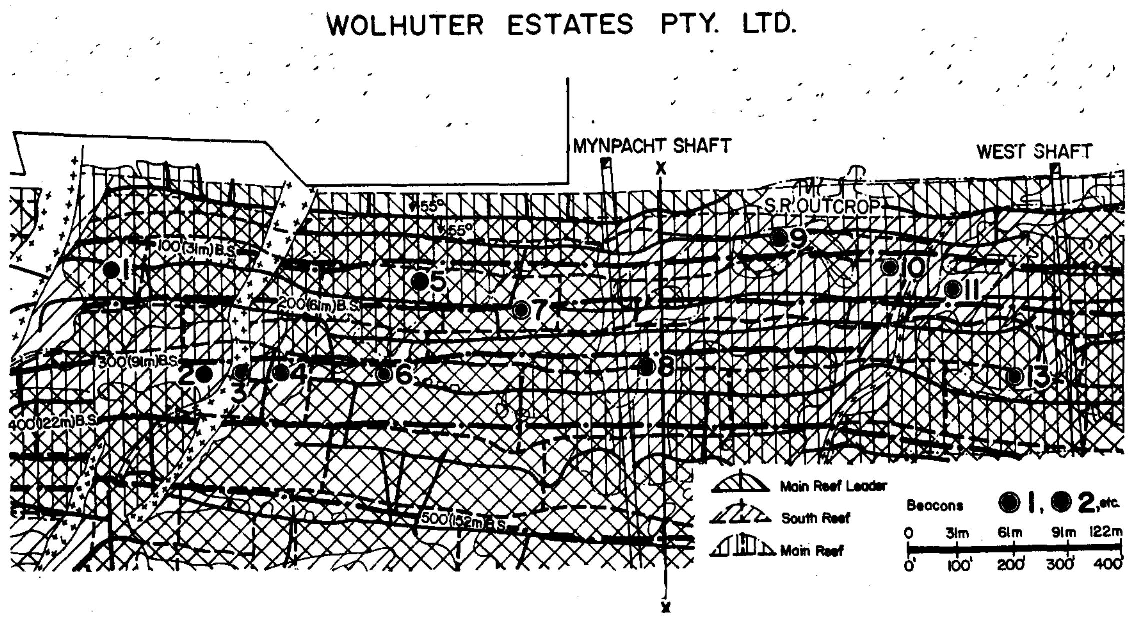


Fig. 51—Sites of the beacons in relation to the underground workings, Wolhuter (zone E); to be noted is the extent of the stoping on the different reefs

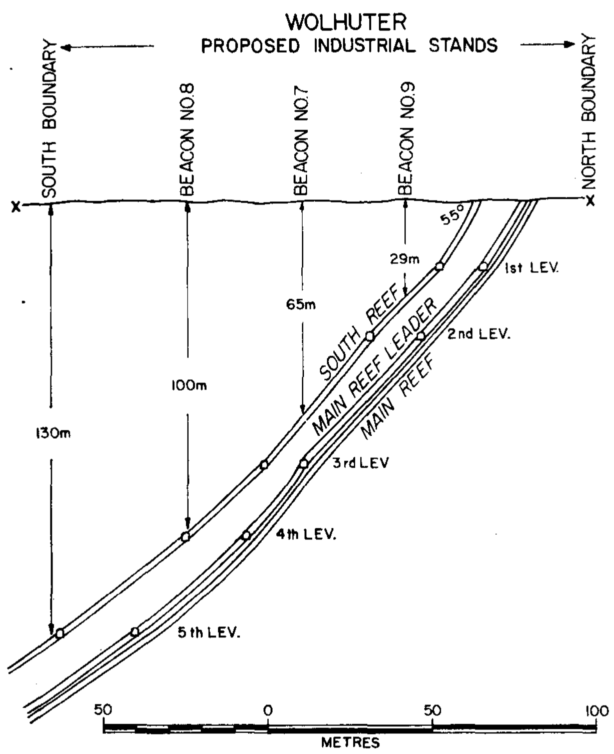


Fig. 52—Section through X-X in Fig. 51 (Wolhuter, zone E)

TABLE X

MONITORING SURVEYS AT STANHOPE, ZONE G

Beacon no.	Progressive rise (+) or fall (−), mm				
	Initial survey Mar. 1975	Apr. 1977	Jan. 1979	Aug. 1979	Jan. 1980
1	0	−15	0	−160	−160
2	0	−30	0	−186	−186
3	0	−18	−30	−131	−131
5	0	+15	−3	−35	−35
6	0	+31	0	−155	−158
7	0	0	0	−172	−177
8	0	+15	−15	−79	−79
9	0	0	+15	−117	−119
10	0	0	+15	−128	−133
11	0	−17	+15	−42	−42
12	0	0	0	−73	−73
13	0	+15	+15	−94	−94
14	0	0	0	−24	−24
15	0	−15	−15	−103	−103
16	0	−15	0	−69	−71

taken place, a readily understandable phenomenon because the combined stoping width of the three reefs mined was 3,5 to 5 m, and the dip of the reefs was flat (10° to 15°). The condition of the hangingwall strata is thus similar to that portrayed in Fig. 31, except that, because of the high stoping width and shallow dip of the reefs,

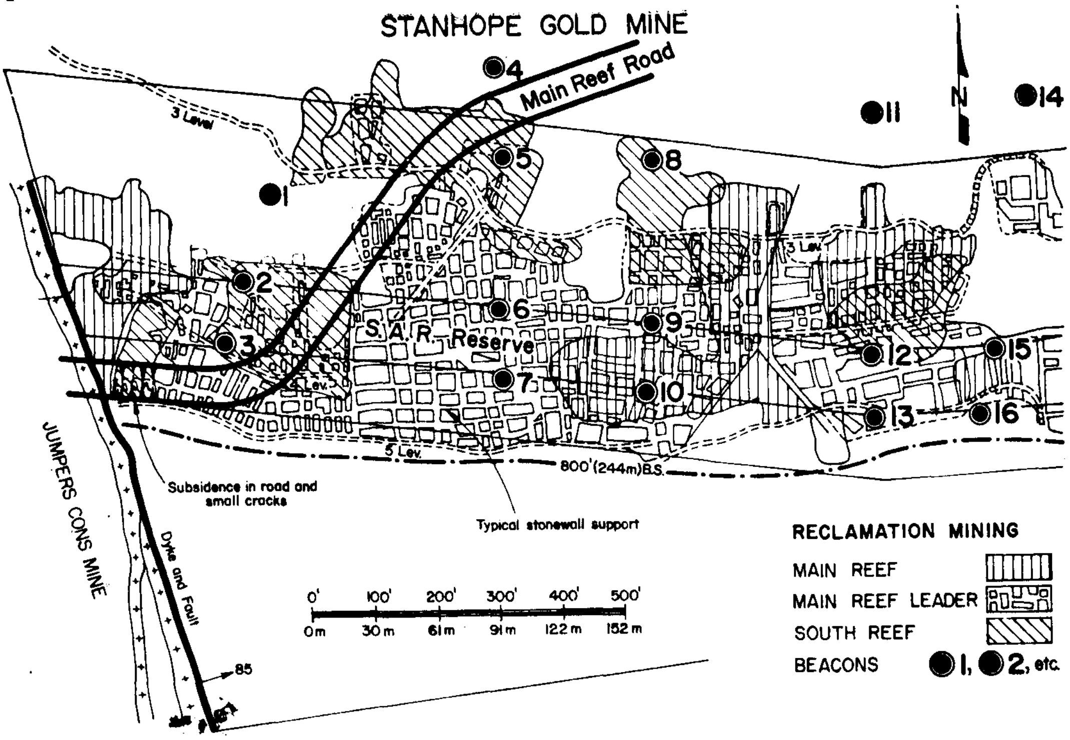


Fig. 53—Plan of Stanhope Gold Mine (zone F), showing beacons in relation to the South African Railways Reserve, the Main Reef Road, and the reclamation mining that has taken place during the past ten years

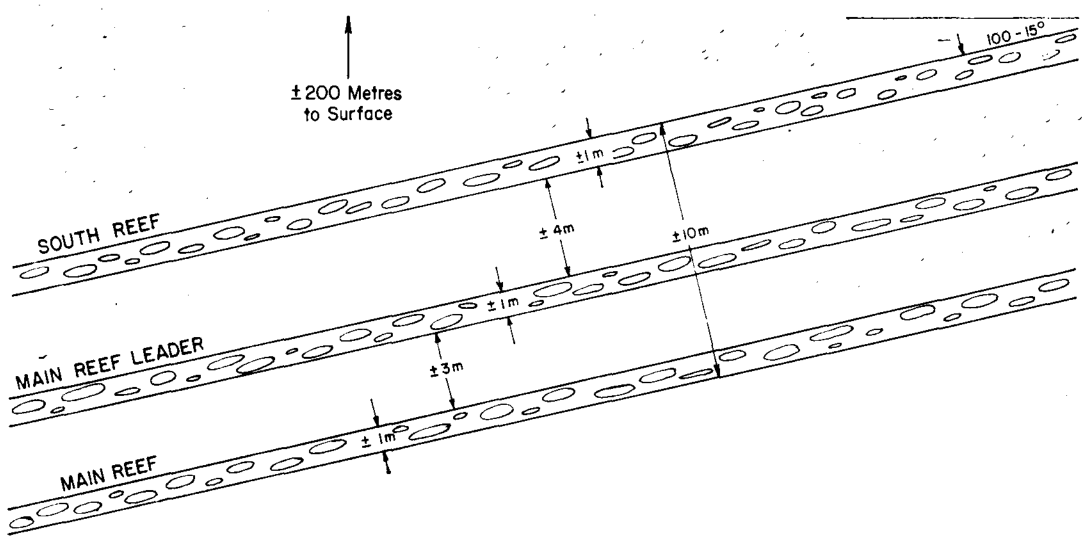


Fig. 54—Section through reefs prior to stoping, Stanhope Gold Mine (zone F)

tension cracks are probably more numerous, bed separation extends into the hanging further than normal, and falls of ground into the stopes are greater.

Conditions in the Stopes Prior to Reclamation. In May 1980 the writer went underground at the Stanhope Mine to examine the areas where reclamation work was in progress. He found them much as he had expected: compressed supports, low reef drives, pillars here and there, falls of hanging in open stopes, and every evidence of subsidence, including places where the hangingwall was resting on the footwall. Fig. 54 shows the virgin reefs, and Fig. 55 reflects the underground situation in the stopes at the time of inspection. The closure of the stopes resulted from mining in the pre-1925 era. As mining progressed, the hanging above the stopes subsided and fractured, and this continued long after mining had ceased. In the process, the stonewall supports and falls of hanging were compressed, and in some stopes the hangingwall reached the footwall; with the passage of time, the fracture zones above the stopes were also compacted and the multitude of diverse supports became more and more compressed until a state of equilibrium was reached. This was not an uneasy state: it was permanent and stable because of the widespread nature of the supports, which consisted mainly of stonewalls and sandfilling. This judgment is based, not only on the observations at Stanhope, but also on the data collected from zones A to I, which show convincingly that, when mining ceases, subsidence slows down until a state of permanent stability is reached. Conversely, if mining is resumed, subsidence may well occur, as shown by the records from Crown Mines.

It appears, then, that the reason for the renewed settling of the strata under the railway line and the Main Reef Road is reclamation work by the Stanhope Mine, which has been in progress in the area for the past sixteen years, and which, for the past five years, has been close to the dyke shown in Fig. 53. This diagram gives a clear picture of the extent of reclamation mining below the Main Reef Road and the railway line on the South Reef, the Main Reef Leader, and the Main Reef. The reclamation consisted, *inter alia*, not only in the removal of pillars here and there, but also in the stripping of reef bands left in hangingwall or footwall, and blasting out or breaking of rock to retrieve the fines, e.g., where hangingwall and footwall met. The effect of these operations has been to reduce the effective overall support in the area; small wonder, then, that the hangingwall mass was once more set in motion, resulting in renewed subsidence on surface as well as downward movement of the hangingwall in the stopes. The differential settlement to be seen on the Main Reef Road(Fig. 53) is not unexpected since it took place on the edge of a dyke.

The strata east of the dyke will probably continue to subside while mining is in progress. However, this is no cause for concern since the Stanhope Mine is providing stonewall support in 60 to 70 per cent of the reclaimed areas. The rate of subsidence will thus be so steady and slow that neither the railway nor the road authorities will have to contend with a problem more serious than that of adding extra ballast under the railway line or levelling out any dip in the road with road-surfacing material.

Zone H – Geldenhuis

In the early days of mining on the central Witwatersrand, when mining depths were still less than 244 m, there was widespread subsidence and fracture of the strata that had been undermined. As mentioned for the Stanhope Zone, of no area was this more true than that of the Geldenhuis Estates Mine, particularly that portion lying to the north of the railway line between Cleveland and Geldenhuis stations. References to fracture and

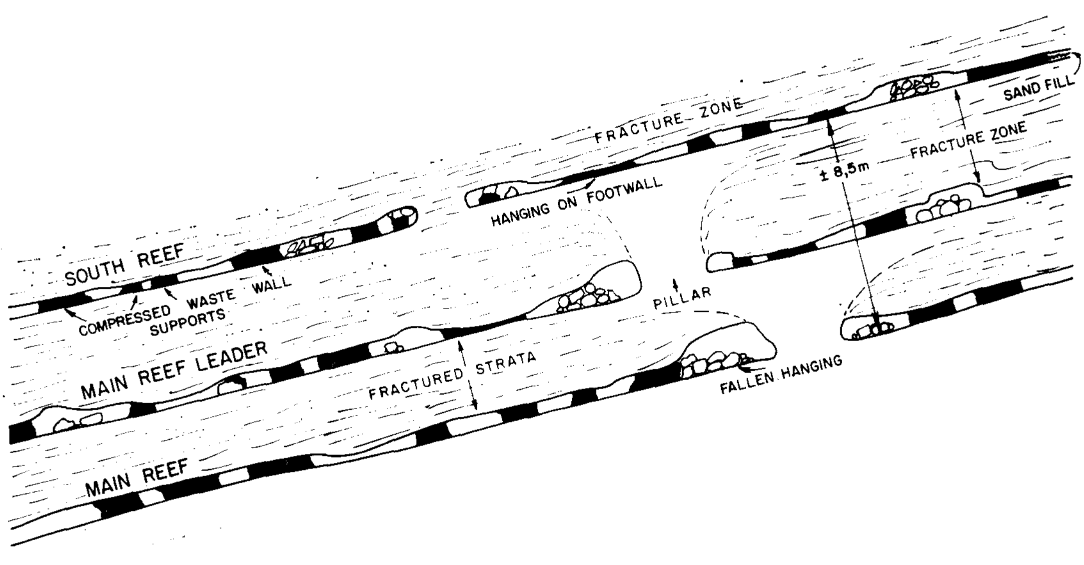


Fig. 55—Present conditions in the stopes of the mined-out reefs shown in Fig. 54; the initial mining took place before 1925

GELDENHUIS ESTATES

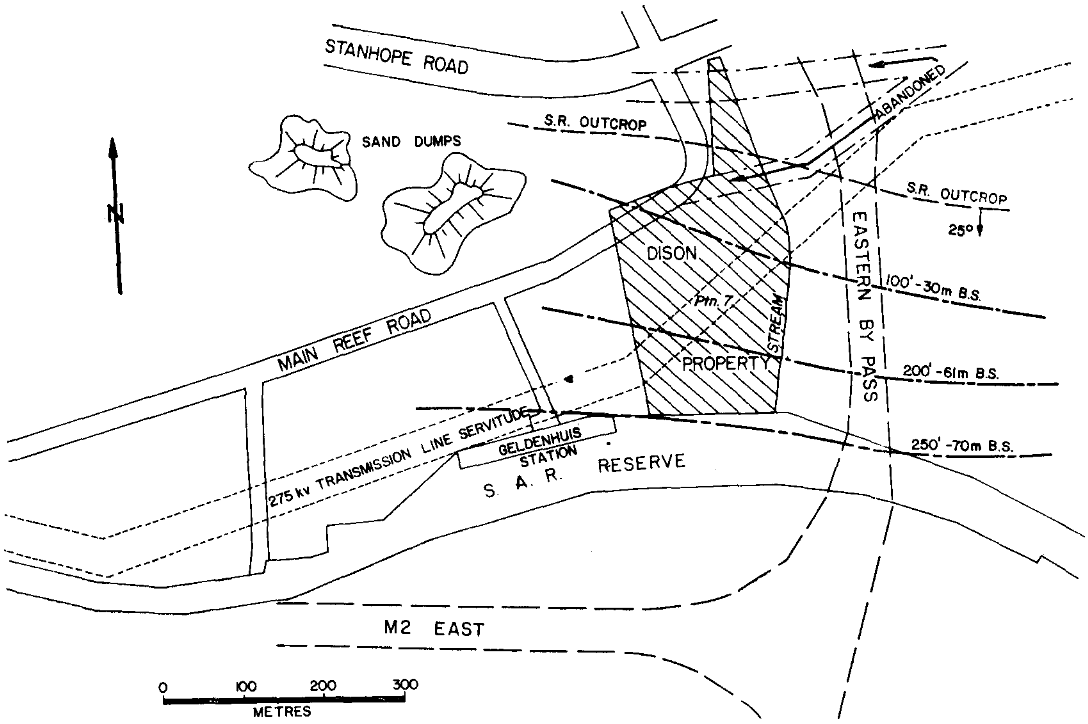


Fig. 56—Plan of Geldenhuis Estates (zone H), showing the depth of the South Reef workings under the Dison property

TABLE XI

MONITORING SURVEYS AT DISON PROPERTY, ZONE H (GELDENHUIS ESTATES)

No. of benchmark, beacon, or turning point	Cycle no. 1 (8.10.77) elevation, m	Cycle no. 2 (17.12.78) elevation, m	Cycle no. 1 minus cycle no. 2, mm
BM	100,0000	0,9977	−2,3
BM (E72OA)	105,3712	0, 3699	−1,3
BM	91,7614	Destroyed	
BM	97,3885	0,3869	−1,6
T1	99,5224	0,5038	−18,6
T2	100,5828	Destroyed	
T3	102,5088	0,4947	−4,1
T4	98,4102	0,4031	−7,1
S	103,3291	0,3279	−1,2
N	104,2540	0,2472	−6,8
E	104,5510	0,5453	−5,7
1	99,4566	0,4146	−42,0
2	98,9789	0,9540	−24,9
3	99,6048	0,5680	−36,8
4	99,9139	0,9002	−13,7
5	100,9575	0,9566	−0,9
6	100,5957	0,5924	−3,3
7	100,4839	Destroyed	
8	103,2520	Destroyed	
9	103,6898	Destroyed	
10	102,4171	Destroyed	
11	100,7299	0,7287	−1,2
12	99,2252	0,2244	−0,8
13	97,6380	0,6361	−1,9
14	94,8832	0,8833	−40,1
15	92,4188	0,4177	−1,1
16	96,8982	Destroyed	
17	99,6952	Destroyed	
18	100,9379	0,9349	−3,0
19	102,6719	0,6688	−3,1
20	104,7007	Destroyed	
21	104,5212	0,5194	−1,8
93	100,1899	0,1658	−24,1
94	100,1889	0,1386	−50,3

TABLE XII

GENERAL SUBSIDENCES DURING SEPTEMBER 1977 TO DECEMBER 1978, GELDENHUIS ESTATES (ZONE H)

Point no.	Subsidence, mm	Point no.	Subsidence, mm
BM	2	S	1
12	1	21	2
11	1	N	7
T3	4	E	6
BC	1	6	3
BM	2	5	1
T4	7	13	2
18	3	14	0
19	3	15	1

subsidence in this area occur frequently in the Government Mining Engineer's reports from 1903 to 1930.

In 1977, the owners of a 9 ha site north-east of Geldenhuis station were desirous of selling their ground, but appreciated the fact that would-be buyers would be discouraged by the building restrictions laid down by the Department of Mines. The owners therefore agreed to a monitoring project to determine whether surface settlement had finally ceased. The survey work was entrusted to Professor I. B. Watt, who used 34 benchmarks and turning points for his measurements. The site monitored is shown in Fig. 56, and the localities of the benchmarks are shown in Fig. 57. Table XI shows the results obtained.

The most significant feature of these results is the indicated overall stability of the area, as reflected in the results given in Table XII.

However, there are a number of points east and north-east of BM where the subsidence was appreciably higher, as shown in Table XIII.

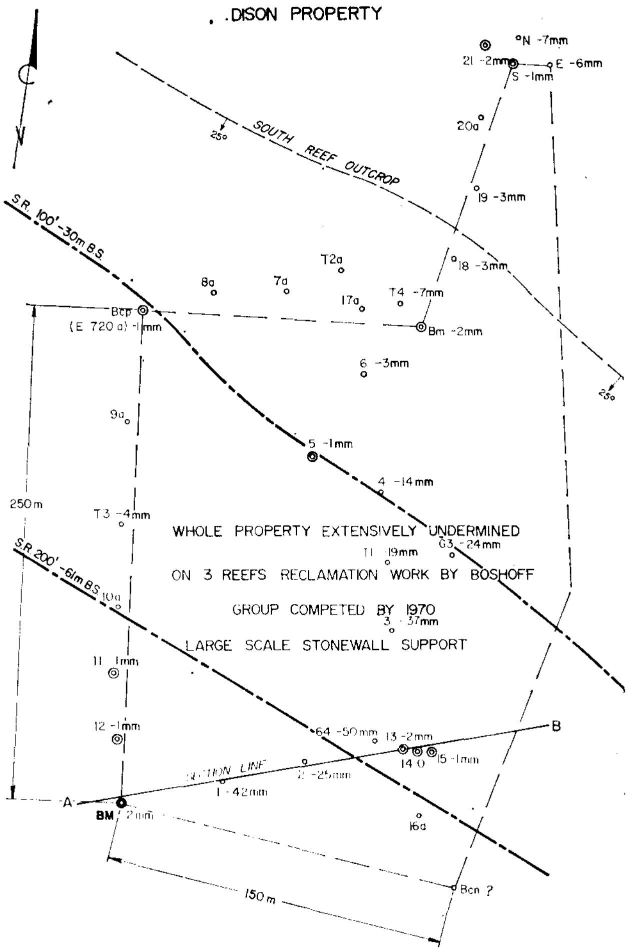


Fig. 57—Location of the beacons or benchmarks established on the Dison site, Geldenhuis Estates (zone H)

TABLE XIII

SUBSIDENCES DURING SEPTEMBER 1977 TO DECEMBER 1978, GELDENHUIS ESTATES (ZONE H)

Point no.	Subsidence, mm
1	42
2	25
G4*	50
3	37
T1	19
G3	24
4	14

*Large white beacon put in by Roads Department.

The unexpectedly high subsidences of Table XIII are attributable to gradual compaction of the soil and are, in the writer's view, unrelated to mining. The Germiston Municipality dumped material on the site about nine years ago, and it is the gradual compaction of this material that has caused the subsidence of the benchmarks (Fig. 58). Points 1, 2, and G4 subsided an average of 32 mm, whereas the average for BM13, 14, and 15 was only 1 mm. This seems clear evidence that the recently dumped material is still compacting, while the main rock mass is stable.

Additional evidence of the stability of the surface is that a large sewer line traversing the site has remained undisturbed since its installation over twenty years ago. Today, then, this once-active area lies at rest: substantial stonewalling and sandfilling have been done, and, in the reclamation work by the Boshoff Group, stonewalls provided the support for a high percentage of the stoped-out area. With the passage of time, the subsiding ground has compressed the supports until there is no more meaningful subsidence; furthermore, because stresses and tensions in the rock mass have been relieved by the early rupture of the strata, surface fracturing appears to have ceased.

Zone I – Rietfontein Consolidated

The site of this defunct mine is shown in Fig. 59. On the western side of the property, the dip of the reefs is steep, but it decreases towards the east to nearly zero. These south-dipping reefs are cut off at a depth of some 365 m by a very large fault, and the total area underlain by the reefs is some 600 ha. Geologically, the mine is 'an outlier', lying 8 km north of the outcropping gold-bearing reefs near Boksburg.

Mining operations ceased in 1967, and the mining group concerned disposed of its freehold rights, the purchasers having been advised by the Group of the Govern-

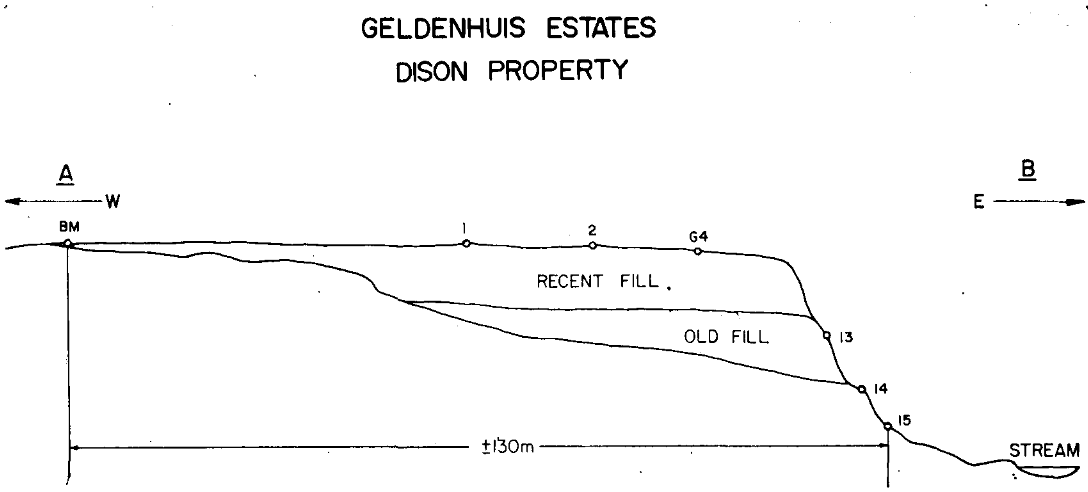


Fig. 58—Section through A–B of Fig. 58 (Geldenhuis Estates, zone H), showing beacons that have subsided on ground where there has been a 'fill' of soil and rock

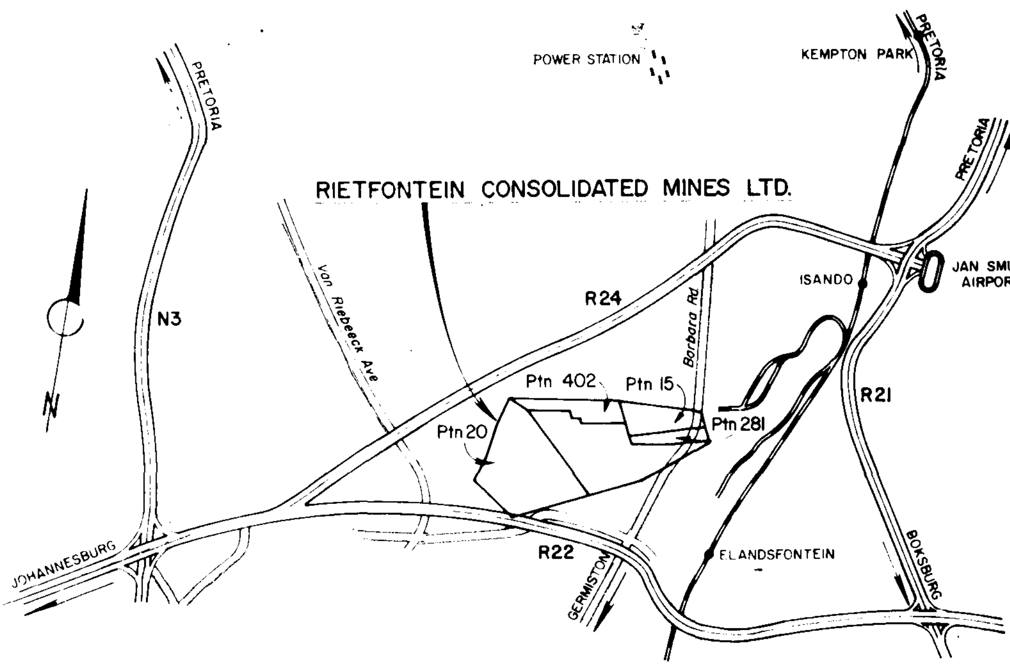


Fig. 59—Plan showing location of Rietfontein Consolidated Mines (zone I)

ment Mining Engineer's restrictions on the use of ground in which the depths of undermining were less than 244m. The companies that acquired portions 20, 402, 15, and 281 of the property (Fig. 59), who were the most affected by these restrictions, commissioned the writer to investigate the stability of the ground; he recommended the same programme as was followed in other areas undermined at shallow depths: firstly, a study of the mining situation (reefs mined, stoping widths, support, and so on); secondly, the drilling of holes to determine the depth of weathering and general competence of the strata; and, thirdly, the monitoring of a large number of surface beacons to ascertain whether subsidence had ceased.

The 'mining situation' was found to be such that little surface subsidence was to be expected: in only a small portion of the property had three reefs been mined, and many large pillars had been left; furthermore, stone-walling was the method of support, adding to the 'stability' factor of the mine. The diamond drill-holes showed the hangingwall rock to be composed of strong quartzites, which are highly competent.

This information, although important, is secondary to the essential subsidence data required for an assessment of the surface stability of portions 20, 402, 15, and 281. To acquire these data, the firm of Greenwood and Arnold, Land Surveyors, was employed to establish beacons on

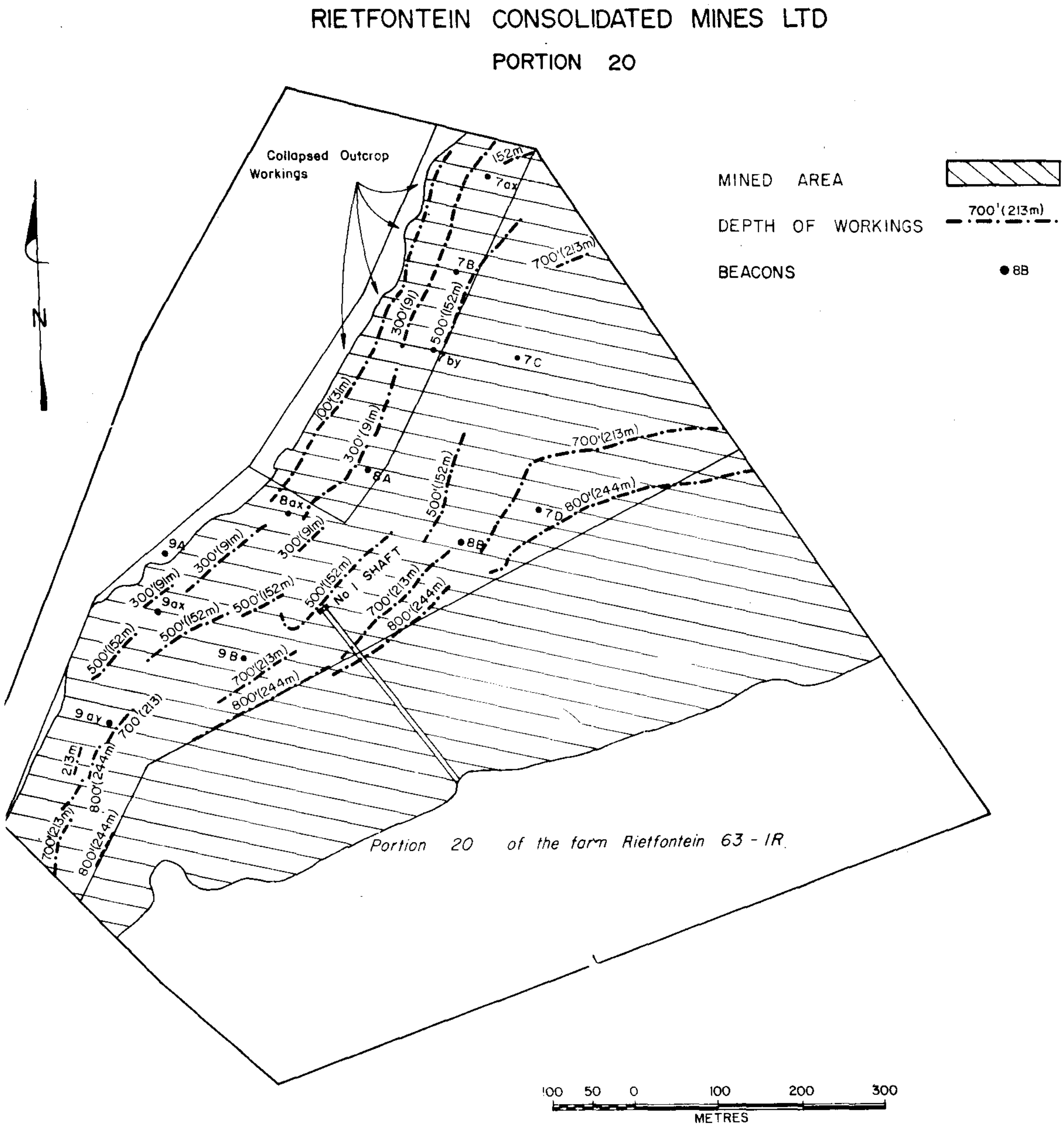


Fig. 60—Plan of position 20, Rietfontein (zone I), showing beacons and depth of mine workings

all four portions and do the subsequent survey work.

Portion 20. Fig. 60 shows the locations of the beacons, which for all these portions consisted of a steel bar projecting from a concrete block embedded to a depth of about 1 m into the soil. Monitoring conducted over a period of six months gave the results listed in Table XIV. It will be seen that the whole of portion 20, whether the depths of undermining are shallow or deep, is completely stable. The few beacons that show differences in elevation of 3 mm are not significant; such small differences are more attributable to soil conditions than to strata movement. Further strong evidence of the hangingwall stability and its *en masse* movement is the fact that No. 1 shaft (Fig. 61), despite being above the mined reefs, was not distorted or in any way adversely affected by movement of the surrounding rock.

Portion 402. This portion lies in the central section of the mine, where the reefs are relatively flat and do not outcrop to surface. The greatest depth of undermining is 180 m, compared with the maximum depth of 370 m reached in the areas to the south. The underground officials who worked in the mine state that the support policy was extensive stonewalling, especially where two or more reefs were mined. Underground inspections have confirmed that the area has been widely and effectively supported by stonewalls. Survey beacons were established, one north of the outcrop and the rest above mined areas, as shown in Fig. 62. The results of the monitoring of these beacons are given in Table XV. The results suggest that, during the period October 1972 to

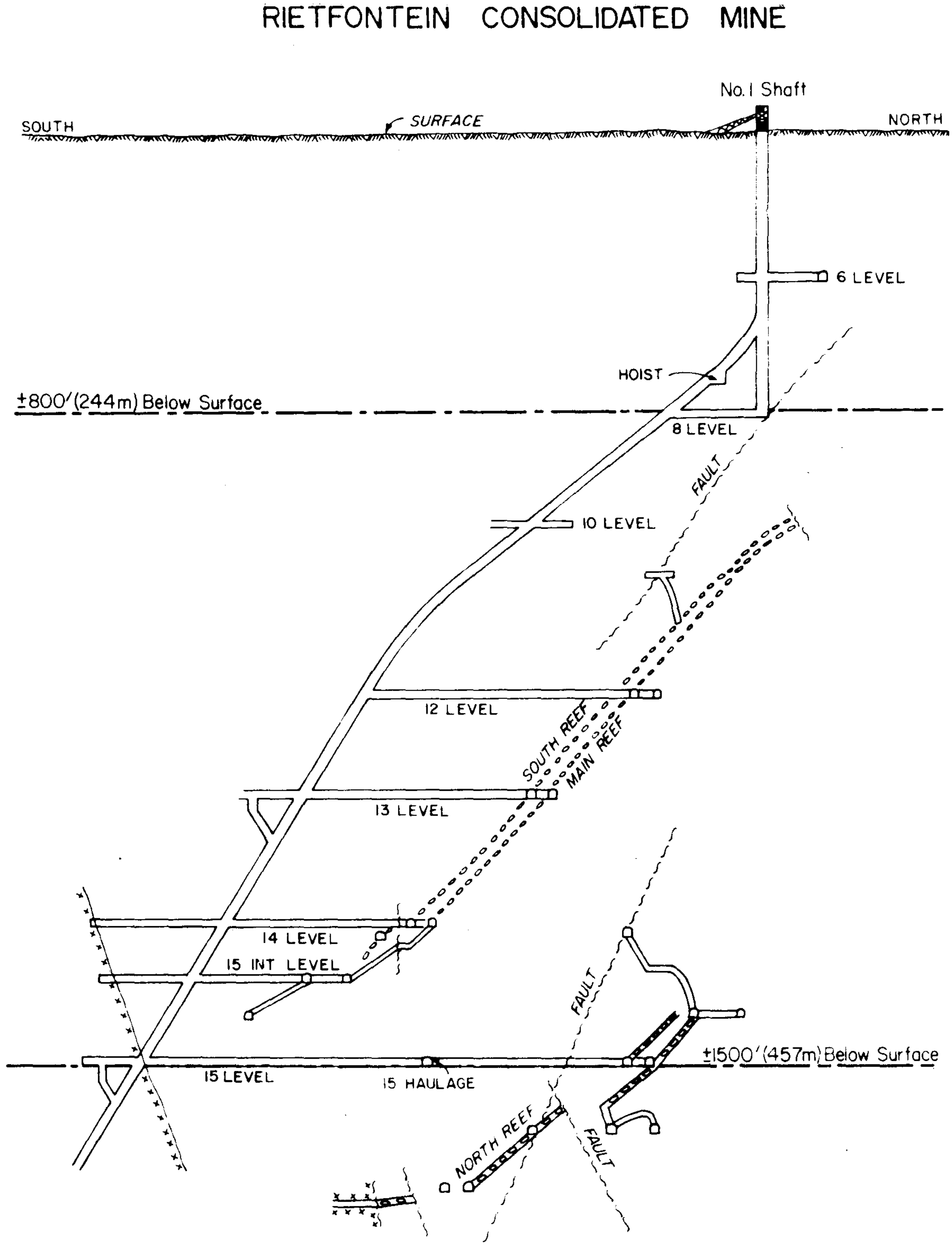


Fig. 61—An incline shaft that was unaffected by the South Reef stoping below, Rietfontein (zone I)

TABLE XIV

MONITORING SURVEY OF PORTION 20, RIETFONTEIN (ZONE I)

Beacon no.	Aprox. depth to mined reefs	Elevations below datum (6000 ft above sea level)		Rise+ Fall−	
		January 1974	June 1974		
	m	ft	ft	ft	mm
R.T. 286	Above	285,529	285,524	+,005	2
R.T. 319	unmined	284,285	284,284	0	0
R.T. 320	ground	284,969	284,969	0	0
7A		422,936	422,932	0	0
7ax	120	355,078	355,088	−0,01	−3
7B	130	365,406	365,414	−0,01	−3
7bx	120	379,450	379,454	0	0
7by	150	393,424	393,424	0	0
7C	180	357,127	357,130	0	0
7D	230	343,149	343,152	0	0
8A	120	389,175	389,181	−0,01	−2
8ax	80	406,518	406,521	0	0
8B	200	367,525	367,529	0	0
9A	30	430,364	430,367	0	0
9ax	120	414,596	414,597	0	0
9ay	210	402,470	402,474	0	0
9B	200	354,704	354,709	−0,005	−2

TABLE XV

MONITORING SURVEY OF PORTION 402, RIETFONTEIN (ZONE I)

Beacon no.	Approx. depth to mined reefs, m	Elevation*, ft		Rise(+) or fall(−)		Elevation*, ft		Rise (+) or fall (−)	
		Oct. 1972	April 1973	ft	mm	Oct. 1973	April 1974	ft	mm
5A	North of outcrop	397,26	397,26	0	0	397,26	397,26	0	0
5ax	110	353,34	353,35	−0,01	−3	353,35	353,35	0	0
5ay	110	—	—	—	—	356,39	356,39	0	0
5b	110	348,47	348,50	−0,03	−9	348,50	348,51	−0,01	−3
5B	120	344,26	344,29	−0,03	−9	344,30	344,29	+0,01	+3
4ax	80	356,28	356,30	−0,02	−6	356,30	356,30	0	0
4B	110	350,30	350,33	−0,03	−9	350,33	350,34	−0,01	−3
Average subsidence				−0,02	−7			−0,002	−1

*Below datum.

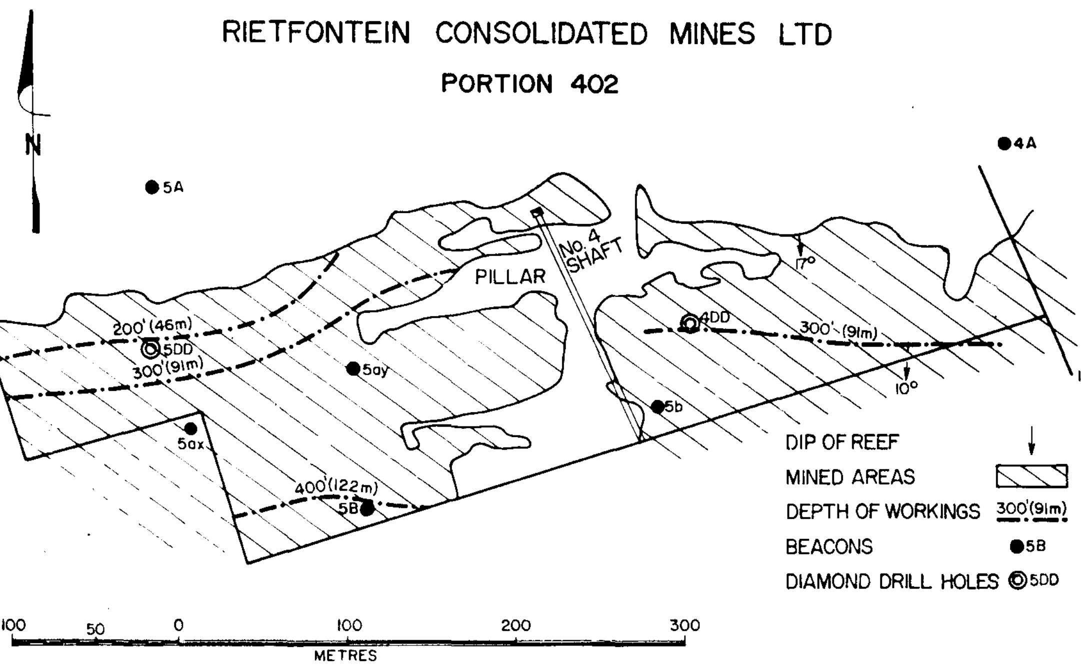


Fig. 62—Plan of portion 402, Rietfontein (zone I), showing the beacons installed on surface and the depth of the workings

April 1973, very slow subsidence was taking place. For a similar period later on, from October 1973 to April 1974, the rate was even less. These results are similar to those obtained at the Ferreira Estate parking ground, where subsidence was seen to be *en masse*, and an already slow rate was steadily decreasing. The amounts of subsidence are negligible, and such conditions pose no risk to life, limb, or property.

Portions 15 *and* 281. The subsidence surveys on these portions gave the results shown in Table XVI.

Perusal of the 'Rise or fall' columns in Table XVI reveals that the whole of the area covered by portions 15 and 281 is almost 'as steady as a rock'; the movements that have taken place are only about 0,01 to 0,02 ft, i.e., about 3 to 6 mm. None of the installed beacons has moved sufficiently to damage surface installations or to present a danger to persons. Beacons 2aNW, 2aSW, and 2A, situated in the north-central section of Fig. 63, are of special interest because they have not subsided even though they lie between the tension cracks shown and the outcropping reefs to the north; this area might normally be regarded as 'suspect', and yet, despite being 'detached' from the main rock mass to the south, it too has come to rest. Another significant beacon is 2B, located roughly in the middle of the mined area. Although three reefs have been mined under this beacon, it has stopped settling, which is further evidence that, after the cessation of mining, subsidence of the hangingwall is eventually arrested.

Buildings Erected on Undermined Ground

The subsidence data presented in this paper are not the only indications that, with time, undermined ground

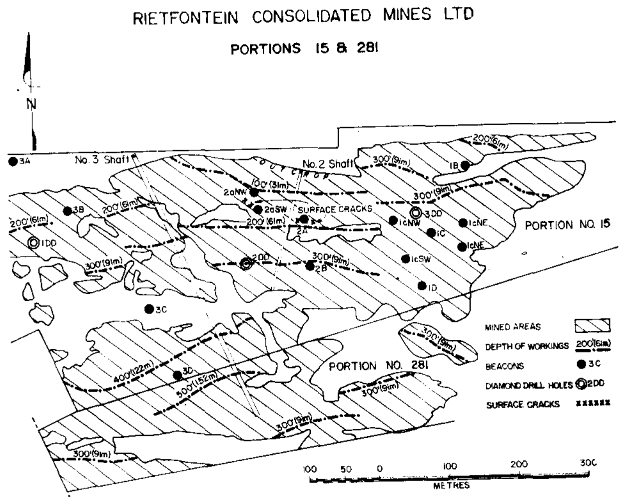


Fig. 63—Plan of portion 15, Rietfontein (zone I), showing the beacons installed on surface and the depth of the workings

TABLE XVI

MONITORING SURVEY OF PORTIONS 15 AND 281, RIETFONTEIN (ZONE I)*

Beacon no.	October 1972 ft	April 1973 ft	Rise (+) or fall (−) ft	October 1973 ft	Rise (+) or fall (−) ft	April 1974 ft	Rise (+) or fall (−) ft
RG7	416,85−	416,86−	0,01−	416,86−	0,00−	416,88−	0,02−
RG9‡	326,09−	326,09−	0,00−	326,11−	0,02−	326,06−	0,05
RT289	338,59−	338,59−	0,00−	338,60−	0,01−	338,59−	0,01
RT290	335,65−	335,65−	0,00−	335,65−	0,00−	335,65−	0,00−
RT294	321,20−	321,20−	0,00−	321,22−	0,02−	321,20−	0,02
1A	354,88−	354,89−	0,01−	354,89−	0,00−	354,90−	0,01−
1B	346,16−	346,16−	0,00−	346,16−	0,00−	346,16−	0,00−
1C	345,47−	345,47−	0,00−	345,48−	0,01−	345,49−	0,01−
1D	347,64−	347,64−	0,00−	347,65−	0,01−	347,66−	0,01−
1E	350,61−	350,61−	0,00−	350,63−	0,02−	350,63−	0,00−
1F	343,44−	343,44−	0,00−	343,46−	0,02−	343,45−	0,01
1cNW	343,20−	343,20−	0,00−	343,21−	0,01−	343,22−	0,01−
1cNE	345,87−	345,87−	0,00−	345,88−	0,01−	345,89−	0,01−
1cSW	345,89−	345,89−	0,00−	345,90−	0,01−	345,90−	0,00−
1cSE	347,18−	347,18−	0,00−	347,19−	0,01−	347,20−	0,01−
1Dx				344,87−		344,87−	0,00−
2A	345,73−	345,73−	0,00−	345,74−	0,01−	345,75−	0,01−
2B	342,89−	342,89−	0,00−	342,89−	0,00−	342,89−	0,00−
2C	350,14−	350,14−	0,00−	350,15−	0,01−	350,14−	0,01
2aNW	349,24−	349,24−	0,00−	349,25−	0,01−	349,25−	0,00−
2aSW	348,19−	348,20−	0,01−	348,20−	0,00−	348,21−	0,01−
2Bx				345,46−		345,46−	0,00−
2PD				350,29−		350,29−	0,00−
3A	378,91−	378,92−	0,01−	378,92−	0,00−	378,93−	0,01−
3B	360,41−	360,41−	0,00−	360,41−	0,00−	360,41−	0,00−
3C	346,69−	346,70−	0,01−	346,70−	0,00−	346,70−	0,00−
3D	345,51−	345,52−	0,01−	345,53−	0,01−	345,53−	0,00−
3E	347,00−	347,00−	0,00−	347,01−	0,01−	347,01−	0,00−
3Bx				354,74−		354,74−	0,00−
3By				352,30−		352,30−	0,00−
3Dx				343,70−		343,70−	0,00−
3Dy				342,61−		342,62−	0,01−

*The elevations are given in English feet below a datum plane 6000 ft above mean sea level.
†The positions of most of the beacons are shown in Fig. 62.
‡This beacon was disturbed during 1973 by a bulldozer.

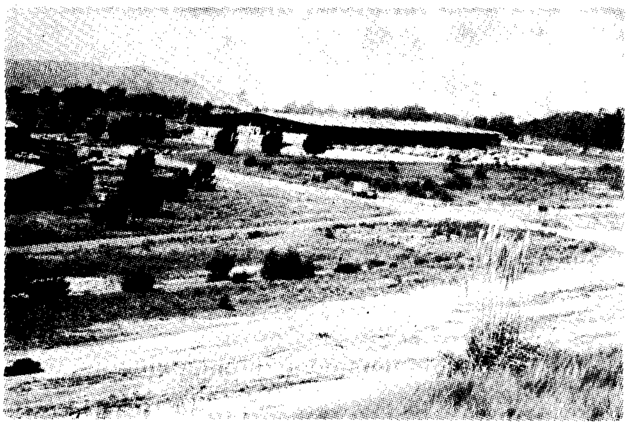


Fig. 64—The warehouse on the old Mayfair Mine

becomes stable. There is, in addition, a great deal of 'visible' evidence to justify this statement: the sound condition of the many buildings that have been erected on ground in the 'restricted building zone', i.e., the zone extending from surface to a depth of 244 m. Examples of such buildings abound, but only three are given here: these are a large wholesale store on the old Mayfair Mine, and shops on two sites in the southern section of Johannesburg.

Fig. 64 is a photograph of the wholesale store, and Fig. 65 shows its position in relation to the underground workings. The outcrop area had been treated as follows before the warehouse was erected. All the rubble and loose material were removed from the throat of the outcrop, and the *in situ* quartzites on the hangingwall and footwall sites were located. The cleared-out area was then backfilled with selected material and compacted. Cables treated with bitumen were next installed to straddle the

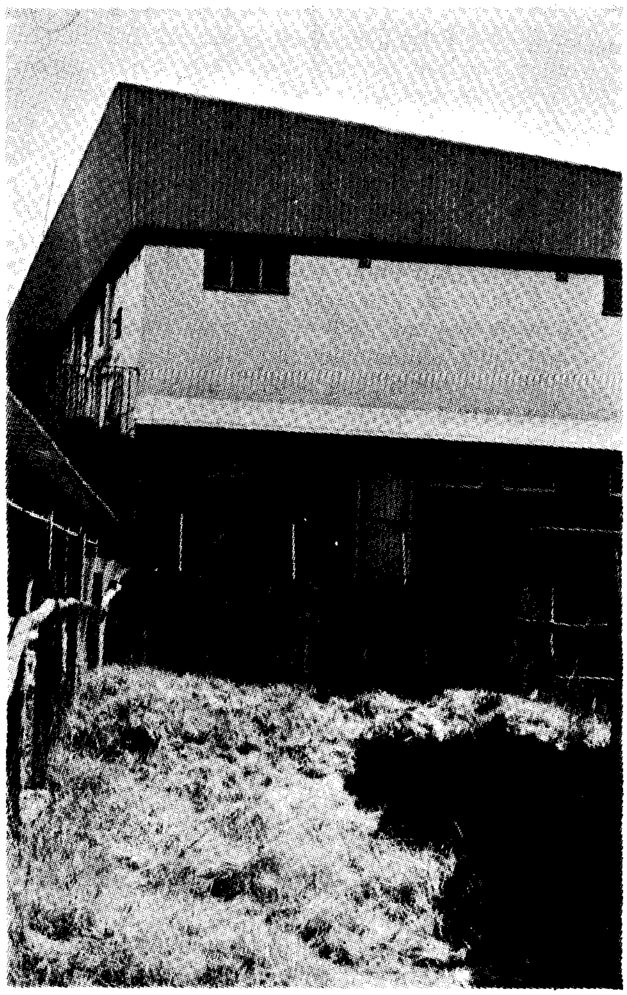


Fig. 66—A sinkhole occurred at the edge of this building (building A in Fig. 69) in 1972 but caused no damage

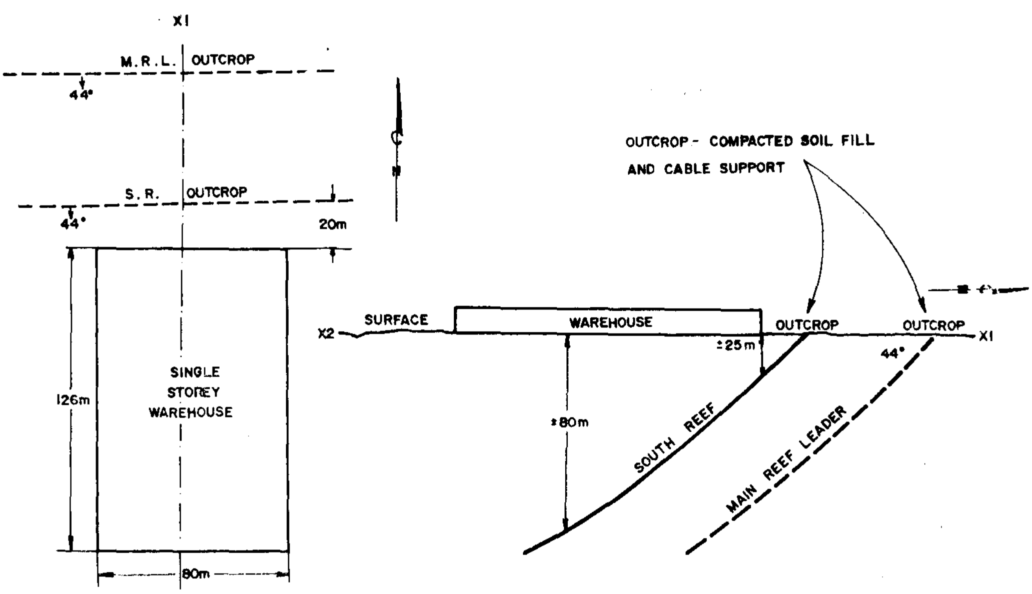


Fig. 65—The position of the warehouse shown in Fig. 64 in relation to the mined-out South Reef

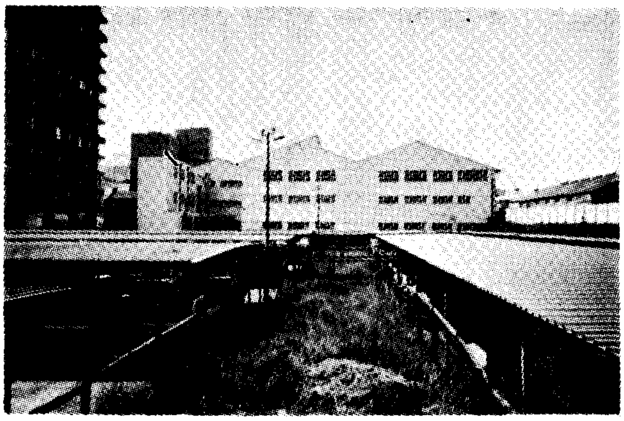


Fig. 67—The fenced-off area next to the building (building B in Fig. 69) marks the strike of the South Reef

sandfilled stopes, and these cables, in turn, were covered with soil to the required levels. The safe-guarding against collapse was carried out so well that the building could have straddled the outcrops without fear of the structure being damaged by any form of subsidence.

Figs. 66 to 68 are photographs of buildings in Hall Street; they rest on reinforced-concrete beams, which span the outcrops. Fig. 69 shows the positions of the steeply-dipping reefs in relation to the buildings.

The two shops of Fig. 70, which were completed in 1975, were erected on ground overlying the outcropping South Reef and Main Reef Leader respectively; they, too, have been unaffected by differential movement of strata, for the reason that the strata have reached a state of rest. Figs. 71 and 72 show the positions of these shops in relation to the reefs.

The South Reef outcrop (and the 170 m depth contour) is shown in Fig. 73. To be noted are the large number of buildings in this 'restricted' zone. Inspection of the buildings has confirmed the absence of damage due to undermining.

Predictability of Surface Behaviour

Two questions arise that are important from a decision-making point of view:

(a) to what extent are further subsidence and fracture predictable in regard to strata that have been undermined?

(b) to what extent would the surface be affected if reclamation mining were to start at depths of less than 244 m?

Surface Behaviour in Relation to Subsidence and Fracture

One of the main reasons for the conservative approach of the Department of Mines in regard to the use of ground undermined at shallow depths is the belief that the future behaviour of the strata is unpredictable. This approach is also characteristic of many civil-engineering firms; because they feel unsure about the stability of the ground, they tend to 'play safe' and provide factors of safety that are unreasonably high and lead to unnecessarily costly designs in structure. The position, as the writer sees it, is that predictability depends on the amount of relevant data available for any particular area. If sufficient data are available, predictions about the future behaviour of the ground are, in most cases, relatively straightforward.

The specific data for the assessment of predictability consist of the mining history of the area. The facts required include stoping widths; support used; presence or

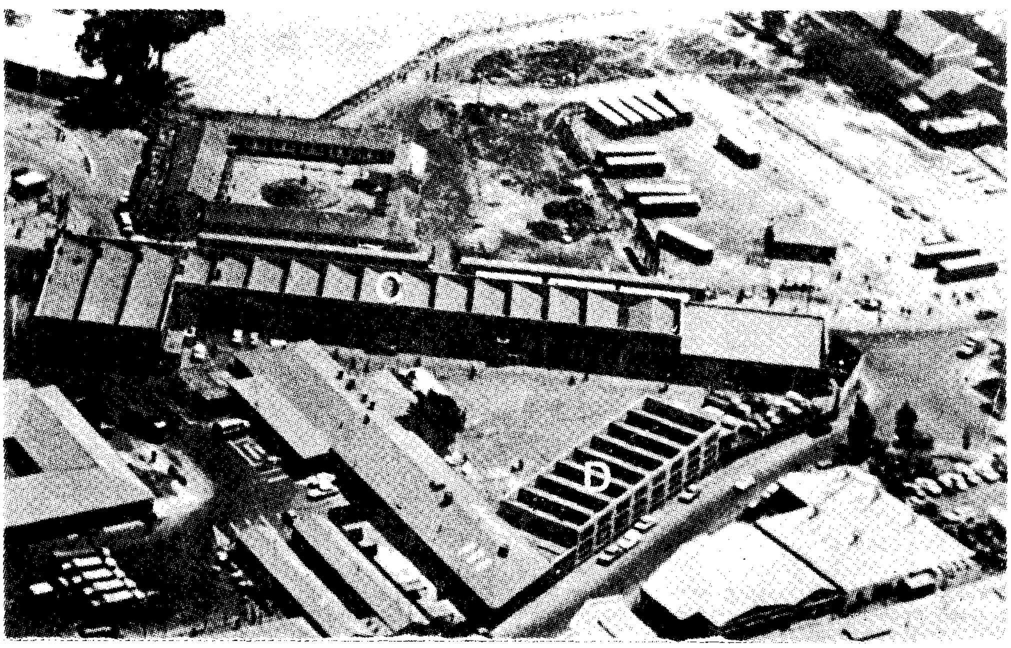


Fig. 68—Despite straddling the Crown Ferreira dyke, these buildings (C and D in Fig. 69), which were erected over 40 years ago, have been unaffected by differential movement of the surface

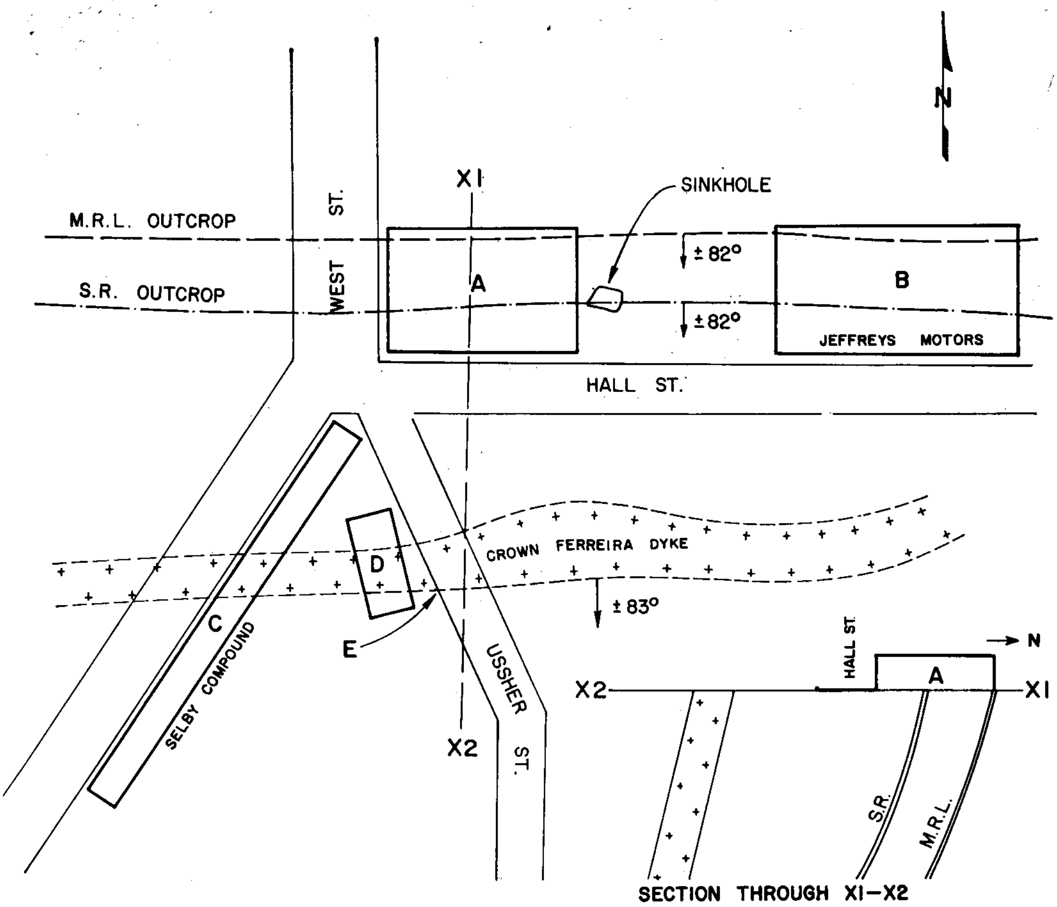


Fig. 69—Plan showing the positions of buildings A to D (Figs. 66 to 68) in relation to the reef outcrops, and a section through building A

Fig. 70—Photographs, looking west, of shops A and B in End Street (Fig. 71), which were erected in 1975 on undermined ground

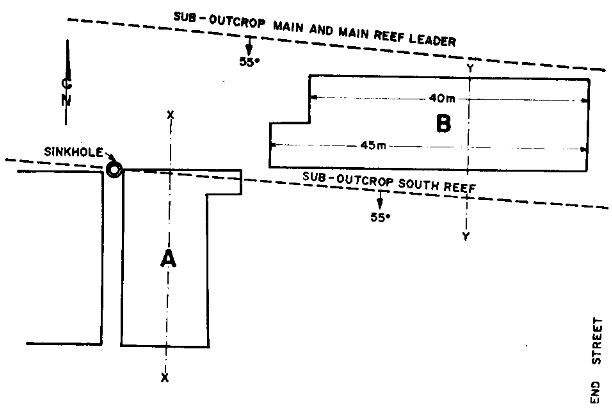


Fig. 71—Plan of shops A and B (Fig. 70) in relation to the South Reef and Main Reef Leader sub-outcrop stopes

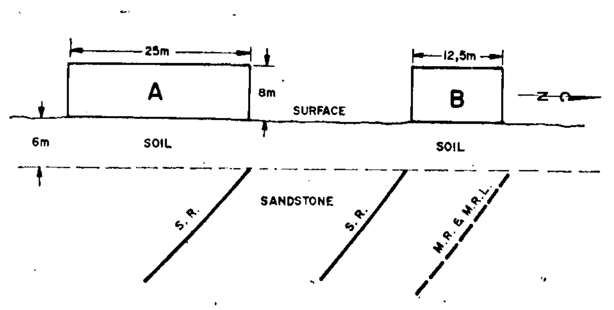


Fig. 72—Sections X-X and Y-Y through shops A and B of Fig. 71 respectively, showing the positions of the stoped-out reefs

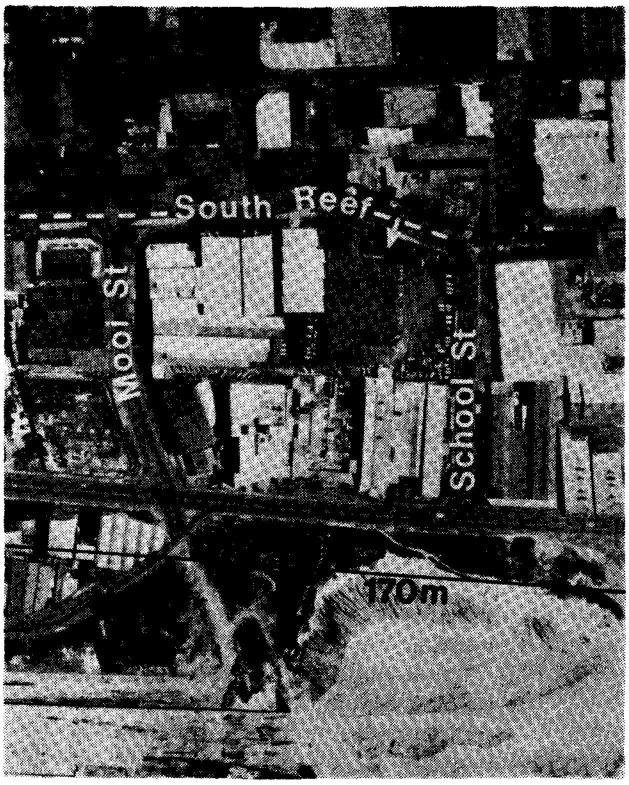


Fig. 73—A large number of buildings where the depths of undermining range from 10 to 170 m

otherwise of pillars, faults, and dykes; and, most important, the date at which mining in the area ceased and the subsidence history of the surface. As a result of the many investigations he carried out during the past ten years, the writer is of the opinion that calculations to predict subsidence, such as those based on the finite element method, have little practical value. The main factors that determine subsidence are so local and variable that they defy a theoretical approach.

Crown Mines. Mining of the upper areas ceased more than twenty years ago, and adequate subsidence records have been kept (Figs. 38, 40, and 42). From this information, the conclusion can be drawn with assurance that further surface movements will be so small that, if buildings are erected, no extra foundation costs need be incurred where the depths of undermining range from 50 to 244 m.

The Ferreira Parking Ground. When reclamation mining was done in this area, stonewalls were the main method of support. Today, some twenty years after mining ceased, the surface is still subsiding, but the subsidence is *en bloc*, the rate is negligibly small (0,7 mm per annum), and is decreasing (Fig. 46). From these data, it can be predicted that, within five years, the rate of settlement will scarcely be measurable.

Wolhuter. Mining ceased at Wolhuter in 1945, and the first subsidence measurements on the property were made by Professor Watt in 1974. The results of the subsidence surveys show that the ground has, substantially, reached a state of rest. It can be predicted that here and there the beacons may subside by a few millimetres, but such measurements are of no practical significance. They would certainly not result in danger to life or property.

Effect of Renewed Mining

There are, unfortunately, very few records available to show how renewed mining at depths of less than 244 m affects the surface, and one has to turn to Crown Mines and the Stanhope Mine for a part answer to this question.

The No. 7 Shaft Traverse Line, Crown Mines. This line (Figs. 40 and 41) overlies an area from which large pillars were removed some thirty years after the initial mining had ceased. The renewed subsidence of the surface covered a wide zone, but was steady and free from shock or fracture. Thus, the Main Reef Road, which passes over this area, showed no signs of disturbance. This fact alone suggests that, had buildings been erected in this zone, they would have subsided, but would have been unimpaired structurally because of the non-differential movement of the ground.

Pylons Traverse Line, Crown Mines. The subsidence along the pylons traverse line (Figs. 42 and 43) was, in places, up to 1,5 m and, as indicated in Fig. 42, some minor cracks appeared on the northern side of the Crown Ferreira dyke. The underground work that caused this surface subsidence was large-scale reclamation mining, most of which was done on the Main Reef. Substantial settlement of the surface was thus inevitable.

Stanhope Mine. Given earlier in this paper are survey results that show how reclamation mining has restarted surface subsidence. They clearly demonstrate the strong link between active mining and strata movement.

The Crown Mines and Stanhope surveys show that reclamation mining, in the sense of removing pillars or weakening other methods of support, may well result in renewed settlement of the surface. Such settlement is normally steady and slow, but, while substantial reclamation could damage surface structures, danger to life cannot be envisaged.

Significance of Data on Subsidence and Fracture

The facts that throw light on the stability and safety of undermined ground should govern the use of that ground. These facts, moreover, should not be those of the 1903 to 1930 era, when mining in the outcrop and upper sections of the mines was causing substantial subsidence and fracture of the strata. They should be the facts that portray the position of the most recent era, stretching, say, from 1965 (when virtually all mining in the outcrop areas had ceased) to 1980.

Such facts as those resulting from the monitoring of zones A to I should be regarded as of major significance. The surveys of those zones covered a distance on strike of some 25 km, and over 320 beacons were monitored; the work was of a high standard, having been conducted by highly competent persons using sophisticated instruments and techniques; the surveys were conducted over a sufficiently long period to give meaningful and positive results.

The survey results from zones A to I demonstrate that

(a) the rate of subsidence decreases with time until, from a practical point of view, the ground reaches a state of rest;
(b) subsidence of the surface overlying mined-out ground is, with few exceptions, *en bloc;*
(c) subsidence is slow and steady;
(d) the amount and rate of subsidence are not directly related to the depth of undermining in the shallow areas under consideration (from surface to 244 m).

These findings should enable decisions on the use of undermined ground to be made with greater assurance than at present. They should, indeed, have an overriding influence on such decisions, and the result would be more scope in the overall planning and development of the surface. The value to the country of a more flexible approach cannot be overrated; the saving in direct and indirect costs could be tremendous, as the following examples show.

Economic Implications

The Western Bypass

The route of this freeway crosses the South Reef and Main Reef Leader outcrops near Wibsey Station. Despite the fact that the C.M.R. Mine ceased mining in these upper areas more than forty years ago, the National Transport Commission (N.T.C.) was instructed to have the stopes under the freeway sandfilled to a depth of 244 m in order to ensure the stability of the freeway. When the costs exceeded R750 000, the N.T.C. became concerned, and asked the writer to investigate the position. A week's inspection of the underground workings, together with his knowledge of the subsidence data from the adjoining zone A, convinced the writer that the sandfilling had been unnecessary. It served little purpose beyond preventing falls of hanging between supports. The judgment that the surface had reached a state of rest has been confirmed by the subsequent monitoring of beacons established along the railway line that crosses the outcrops not more than 100 m from the Western Bypass. A well-designed reinforced road foundation over the outcrops would have ensured a trouble-free crossing, i.e., after any exposed mining voids had been filled in and compacted.

The Extension to Riverlea Township

As already pointed out, there would be great savings in the costs of infrastructure and transport if the whole of the undermined zone from a depth of 50 to 244 m could be used for houses. The short- and long-term savings would almost certainly amount to hundreds of thousands of rands. This is a compelling example of potential cost saving because it illustrates the possibility of greater latitude and thus economy in the regional planning of the long strip of restricted ground stretching from Randfontein to Springs.

Modder B Mine

Over one million rands are reported to have been spent in the sandfilling of a mined area at the Modder B Mine on the East Rand. The object was to safeguard buildings where persons were to be housed, but it is questionable whether this high expenditure was justified, especially as underground mining had ceased more than thirty years before.

Resumption of Mining

Even if reclamation mining were to re-start, e.g., at the Croesus Mine, this should not preclude the building of houses on the surface. The cost of repairing damage to the few houses that might be affected is negligible in relation to the costs saved by full utilization of the site. The question of safety to persons, for reasons already given, does not arise.

Revision of Guidelines

There are in the Mines and Works Act no specific regulations governing the responsibilities of the Department of Mines *vis-a-vis* ground that has already been undermined. This 'vacuum' in the regulations has been filled by conditions or guidelines framed by the Department for its inspectors, who are responsible for recommending the conditions on which structures may be erected on undermined ground. This responsibility is so far-reaching in its economic and social implications that a very strong case exists for the guidelines to be revised. It should not be inferred that the guidelines are never bent; indeed, senior staff of the Department, when given evidence that a site is stable, have not been inflexible but have been highly co-operative. Examples of their flexible approach are provided by the buildings shown in Figs. 64 to 73, which are undermined at depths of far less than 91 m, and by a large four-storey building straddling the outcrops of both the South Reef and the Main Reef Leader, which was erected later. Nevertheless, the existing strictures continue to hamper the most beneficial development of many sites, and continue to frighten property owners who are told that their ground is liable to 'subsidence, settlement, shock, and fracture'.

Conclusion

The logical approach to the revision of the Act would seem to be that the Government Mining Engineer should appoint a Commission – similar to the 1926 Commission on Rockbursts – to gather as much information as possible on the stability of shallowly undermined ground on the Witwatersrand; particularly to be welcomed would be any evidence contrary to that presented in this paper. Having received and studied this information, the Commission would review the present guidelines to see if any changes would be desirable. For example, the collected data would almost certainly confirm that ground undermined at a depth of 50 m is normally as stable as ground undermined at 250 m; again, evidence might convincingly show that, once ground has reached a state of rest, it matters little if dykes or faults are present in the area. To ensure that the Commission's task is undertaken in a professional way, it should include experienced mining men with specialist knowledge of the problems at issue. This knowledge should involve an in-depth familiarity with the factors that influence stability and, among these, subsidence histories should take first place.

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Metallic corrosion

The 8th International Congress on Metallic Corrosion (ICMC) is being held in Mainz from 6th to 11th September, 1981. This is the first time that ICMC is taking place in the Federal Republic of Germany. The DECHEMA—which is organizing the Congress on behalf of a number of international and German societies — has prepared a comprehensive programme of lectures with 10 plenary and 80 discussion papers, as well as about 220 poster papers, to be presented by 300 authors from 41 countries. Every participant will receive the manuscripts as congress documentation at the beginning of the Congress.

The papers deal with the fundamentals of corrosion and practical experiences in different industrial applications.

They include the following:

- Offshore and Sea-water Technology
- Chemical and Petrochemical Industry, and Oil and
- Gas Winning
- Conventional and Nuclear Power Stations
- General Construction, and Water and Central-heating systems

Further information is available from Dechema, Postfach 97 01 46, D 6000 Frankfurt (M) 97, West Germany. Telephone: (0611) 7564–235, telex: 412 490 dchmad.