Iron content in the sphalerites is generally low.

There are minor hydrocarbons developed in the sequence, but none appears to be associated with the mineralization.

Replaced evaporites occur in the carbonates, but it is not known whether the top part of the carbonate stratigraphy in the Zeerust field corresponds to the mottled dolomites in the Intimately-Mixed Dolomite-and-Chert Zone of the Carletonville area.

2. Genetic considerations

In general, the above criteria corresponds well to the ideas of the Mississippi Valley lead-zinc deposits, but Martini (1971) has shown that there are abundant silicate minerals in the Zeerust area, associated with low-grade metamorphic effects. Tremolite, talc, chlorite, phlogopite, and scapolite are common, and these are indicative of temperatures ranging from 400 to 450°C, which are significantly higher than those of the Mississippi Valley-type deposits. A lead-zinc deposit on Witkop Farm, in the Zeerust District, consists of a circular pipe-like body which contains abundant tremolite. Humphrey (1908) suggested that this represented a volcanic conduit, formed as a result of volcanic exhalative activity. Previously, Molengraaff (1898) proposed that the mineralization of the Transvaal dolomite was related to the emplacement of the Bushveld Igneous Complex, a theory which cannot be disregarded. However, Hammerbeck (1970) has argued that, as many of the deposits in the Transvaal display rhythmic layering, much of the mineralization is synsedimentary, but, as the ore is frequently associated with quartz veins and fissures, at least some remobilization has taken place. The presence of rhythmic layering is not necessarily indicative of syngenetic mineralization and may simply reflect the selective replacement of carbonate by the ore minerals. This is similar to the fabrics recorded in this study, where silica has replaced dolomite layers in stromatolite structures.

In many cases, the lead-zinc mineralization in the Zeerust area, and in the northern Cape Province, is associated with manganiferous earth which is developed during weathering of the dolomite (Martini, 1971). In the geochemical analyses of the shales of the Timeball Hill Formation, taken from
Borehole UD30, it was noted that there is a distinct decrease in lead and zinc values as the contact with the chert breccia of the Fountains Formation is approached. This could reflect a depletion resulting from post-depositional groundwater leaching. In the Zeerust area, the shales of the Pretoria Group lie immediately above the Fountains Formation and may have acted as a source-rock for the lead and zinc deposits.

3. Discussion of paragenesis

Petrographic analysis of the Malmani Dolomite Subgroup showed that there have been several episodes of silicification and dolomitization. The carbonates initially underwent a period of dolomitization by alkaline solutions, with a pH of between 8 and 9. In this range of pH values, carbonates are relatively insoluble and are precipitated, but silica and evaporites are soluble and are preferentially enriched in solution. In the presence of sulphate-reducing bacteria and decaying algal matter, the sulphate is reduced to form sulphide, and metal-bisulphide complexes are generated. This assumes that metal ions are present in the carbonates at this point. With increasing time, calcium, magnesium, and carbonate ions are gradually removed from the dolomitizing solution, and, with increasing silica concentrations, the pH falls, and more acid conditions develop. Silicification is favoured, so that some carbonate will be replaced and the metal-bisulphide complexes become unstable and metal sulphides are precipitated. If oxidizing conditions prevail, the metal ions are capable of forming soluble chloride complexes in a saline brine. As the dolomitizing and silicifying processes continue, under fluctuating pH conditions, it is possible for the metal ions to be concentrated and to form an ore-body.

If metal ions are not available in the carbonate system, then an external source must be invoked. It has been suggested that metal ions may be leached from an adjacent shale-source by groundwater during compaction and that, when these metal-enriched solutions encounter a sulphide-enriched brine in the carbonates, the metals are precipitated. This mechanism was proposed by Jackson and Beales (1967) and Beales and Jackson (1967) for Mississippi Valley deposits, and may be responsible for the development of the lead-zinc deposits in the Malmani Dolomite Subgroup. It is significant that, in the Zeerust area, the Malmani dolomite is overlain by the Fountains Formation...
Formation, followed by the shales of the Pretoria Group, and that base-metal deposits are present, whereas in other districts, where the Penge and Duitschland Formations are developed above the Fountains Formation, mineralization is less common. It seems unlikely that the metals were derived from the carbonates, but they could have migrated into the sediments from a landward source, as in Renfro's (1974) model for sabkha-generated metalliferous deposits. The recent paper by Muir (1979) documents a carbonate and mudstone sequence from the McArthur Group, Australia which is analogous to the Malmani dolomite. She has described evidence of replaced evaporites and suggested that, during diagenesis, metal- and sulphate-rich brines moved through the carbonates and eventually contributed to the McArthur River lead-zinc deposit, situated in adjacent shales. These syngenetic and diagenetic processes may certainly have operated in the Malmani dolomite. The recognition of evaporitic horizons is of great importance when considering a precipitating mechanism, however, there is still a distinct possibility that the metals were derived hydrothermally and were associated with the Bushveld igneous activity. Their ultimate concentration might have been related to the formation of sulphide-enriched brines in the carbonates, which precipitated the metals when they were mixed with the hydrothermal solutions. In either case, structural and fracture control would be significant.

Lead isotope data from the Transvaal Supergroup is practically non-existent, but this information is important in recognizing the origin of the lead-zinc mineralization. In the case of the Tsumeb ore-body, in South West Africa, detailed lead isotope data has been used to evaluate base-metal deposit potential (Hughes and Welke, pers. comm. 1980). The data suggests a mixed, heterogeneous source for the lead and this was probably generated in an orogenic environment. The copper- and silver-bearing Tsumeb deposit is situated in the top part of the dolomites of the Otavi Group, which was deposited between 900 and 600 m.y., and, it has been postulated (Hughes, pers. comm. 1980) that, during compaction of the sediment, basinal brines leached metal-ions from the rocks. These solutions contained primary leads and migrated upwards towards the shelf sediments, but were contaminated en route by "mixed" leads remobilized from the underlying sediments which were caught in an orogenic episode. The ore-minerals were precipitated in the Otavi dolomite when they encountered sulphate-enriched fluids. All the copper-lead-zinc deposits of the Tsumeb
district appear to be related to the same process, and a mineralization age of 600 m.y. is given by the intercept of the lead-isochron on the primary growth curve.

It is possible to assess the economic potential of a base-metal deposit by plotting lead isotope data on the trilinear diagram devised by Conran et al. (1961) (Figure 60). Statistically, analysis of the world's major ore-bodies reveals a fairly restricted isotopic field of high probability and, if the isotope data falls in this field, it is likely to be economically important. There are several small deposits from the Zeerust district for which lead isotope data have been obtained (Gallon, 1979), and these have been plotted on Figure 60. They plot slightly outside one of the zones of high economic potential, however, more detailed isotope analyses are required to evaluate the Zeerust deposits. This should help in the recognition of mineralization processes and ultimate source of the ore-minerals in the Malmani dolomite.

F. CONCLUSIONS

The discovery of evaporite horizons in the Malmani dolomite is significant, when examining the future potential for lead-zinc deposits. The evaporites are a suitable source of sulphate ions which, when incorporated in connate brines, function as a transporting medium for metal ions and a reductant for the development of metal sulphides. There are three main theories proposed, to account for the formation of base-metal sulphides in the Malmani dolomite:

(i) During compaction, metal ions were leached from the shales of the Timeball Hill Formation by connate brines. These metal-rich solutions percolated downwards into the porous carbonates, passing first through the chert breccia of the Fountains Formation which may have functioned as an aquifer. Within the carbonates solutions, enriched in \( \text{H}_2\text{S} \) and slightly acidic in nature, were encountered which precipitated the metal-sulphides.

(ii) Metal-ions were concentrated during sedimentation by evaporative-reflux, and mobilized during diagenesis and alteration processes as chloride and bisulphide complexes. Precipitation took place during
silicification when acid conditions, and \( \text{H}_2\text{S} \)-enriched fluids, destroyed the metal-complexes.

In both cases (i) and (ii), the mineralization might have been related to facies change (Type C), sedimentary structures (Type A), or palaeo-solution phenomena (Type B). A tectonic control cannot be precluded, and, since syn-depositional tectonic activity has been demonstrated in the study-area, both small and large scale structures could have influenced the localization of base-metal mineralization.

(iii) Mineralization was hydrothermal and related to Bushveld igneous activity, and the carbonates hosted the ore deposits because they were porous and supplied sulphide ions for the precipitation of the base metals.

Of these three hypotheses the author prefers the first as the mineralizing process.

G. THE DISTRIBUTION AND SIGNIFICANCE OF SOME OTHER ECONOMIC MINERALS

There are several economic minerals present in the Malmani dolomite, which warrant a brief mention, and these are recorded below.

1. Copper

Small grains of chalcopyrite were identified in the borehole core studied, and insignificant copper mineralization has been recorded in association with lead-zinc deposits and the gold-quartz reefs of the Pilgrims Rest-Sabie and Zeerust districts.

2. Fluorite

In the Zeerust area, fluorite deposits are developed with an average grade of 15 per cent \( \text{CaF}_2 \) and an estimated reserve of between 100 and 150 million tons. The deposits occur in pockets, pipes, breccias, and as stratiform bodies, often associated with lead and zinc, in the upper part
of the Malmani dolomite stratigraphy (Crocker and Martini, 1976). The fluorite might have been of hydrothermal origin, related to the Bushveld igneous activity, or might have been leached from the overlying shales of the Timeball Hill Formation.

3. **Gold**

Gold was first discovered in quartz veins in the Pilgrims Rest-Sabie and Zeerust Districts late in the nineteenth century. These occurrences were considered to be hydrothermal, but Minnitt *et al.* (1973) suggested that they were derived from a shale proto-ore in the dolomites.

4. **Limestone**

No limestones have been detected in the dolomite material studied, but there are many small limestone deposits in the Malmani dolomite elsewhere, in both the Transvaal and in the northern Cape. These are mostly thin and discontinuous and have escaped the pervasive dolomitization processes which affected most of the carbonate sediments. Limeacres is the largest deposit in the northern Cape and a deposit at Marble Hall, the largest in the Transvaal.

5. **Manganese**

There are many small manganese occurrences in the dolomites, and there is a background concentration of manganese dioxide of slightly less than one per cent. There are no significant deposits in the Carletonville area, but manganiferous earths and crystalline manganese has been recorded in many localities, particularly associated with palaeokarst surfaces in the dolomite. Most are of low economic importance, except for the large deposits near Postmasburg in the northern Cape.

6. **Pyrite**

Small pyrite cubes are abundant throughout the Malmani Dolomite Subgroup, and amorphous pyrite is frequently concentrated in quartz veins.
There is much pyrite in the black carbonaceous shales, particularly in the Black Reef Quartzite Formation, where framboidal-type pyrite is occasionally developed.

7. Silver

There is a small amount of silver associated with galena. This metal was often recovered during the reduction of galena.

8. Uranium

The presence of uraninite has been recorded in the Black Reef Quartzite Formation, in places where sediment has been derived from the Witwatersrand Supergroup, but only in relatively insignificant quantities.

9. Vanadium

Vanadinite, a chloro-vanadate of lead has been produced as a by-product from the lead-zinc deposits in the Zeerust area.
CHAPTER VI

The Zinc Mineralization on the Western Deep Levels Gold Mine Property, Carletonville, Transvaal
Figure 62: Details of the mineralisation in Borehole UP30, within the Malmani dolomite, on the Western Deep Levels Gold Mine property, Carletonville.
Sphalerite mineralization was intersected in 1977, in the Malmani Dolomite Subgroup, during the drilling of deep gold exploration Borehole UD30, on the Western Deep Levels Gold Mine property, near Carletonville. Further, minor zinc mineralization was subsequently detected in Boreholes UD32 and UD33, drilled to the east and south, respectively, of Borehole UD30. Grades established in the first borehole deflection were economically significant, and it was the purpose of this project to investigate the mode of origin of the mineralization.

B. STRATIGRAPHIC AND GEOLOGICAL SETTING

The zinc mineralization in Borehole UD30 is situated in the Intimately-Mixed Dolomite-and-Chert Zone, approximately 100 metres below the base of the Fountains Formation, and 80 metres above the Upper Laminated Dolomite-and-Chert Zone (Figure 62). In Borehole UD32, galena was detected approximately 100 metres below the Fountains Formation, and, in Borehole UD33, sphalerite was noted at 809 metres, approximately 90 metres below the Fountains Formation. In all the mineralized zones, sedimentary and organic structures were abundant and included ooids, oncoids, flat-pebble breccias, fenestral fabrics, stromatoloids, and small domal stromatolites. Typical intimately-mixed dolomite-and-chert is developed, consisting predominantly of dolomicrite, minor dolosparite, and cryptocrystalline, translucent chert, which is present throughout, and one-metre-thick, mottled, dolomite horizons are developed above and below the mineralized zones. These probably represent the supratidal, upper part of a sedimentary carbonate cycle, which infers that the sulphides are situated in the shallow-water intertidal-to-subtidal facies. The stratigraphic maps presented in Chapter II, indicated the presence of a syn-depositional, north-trending antiform in the vicinity of Borehole UD30 and UD33. This has caused a slight thinning of the Intimately-Mixed Dolomite-and-Chert Zone. During the development of the Fountains Formation this feature also functioned as an antiform, and accounts for the

thin the Mine
increased thickness of the chert-breccia, in Borehole UD30, deposited on
the palaeokarst surface. In all the boreholes, the Malmani dolomite is uncon-
formably overlain by the chert-breccia of the Fountains Formation, which
is, in turn, covered by the black, carbonaceous mudstones and quartz are-
nites of the Homeball Hill Formation. Although several dolerite dykes and
sills are present in the dolomites, none appears to have a close spatial
relationship to the sulphides.

C. SEDIMENTOLOGY

There are abundant sedimentary cycles in the Intimately-Mixed
Dolomite-and-Chert Zone and the prevailing sedimentary environment was
shallow-marine. The presence of mottled dolomite horizons indicates the
development of supratidal conditions, and textures indicative of replaced
evaporites have been detected. In the area investigated, no distinct lateral
facies changes were evident, and the syn-depositional tectonic activity does
not appear to have drastically modified the palaeotopography. Coarse-
grained dolomite zones were not generated, as in the Complex Dolomite Zone,
and, consequently, groundwater refluxing was probably not a major process.
Textures examined in thin-section show a fine-scale, inter-relationship
between silica and dolomite. The silica invariably occupies the core of
individual fenestrae, and this illustrates the gradual filling of an early
porosity, however, there is no indication of distinctive fluid-migration
paths, and, it is difficult to determine whether the dolomitization and
silicification of the Intimately-Mixed Zone took place under mobile or
static conditions.

D. MINERALIZATION

1. Introduction

The mineralization in Borehole UD30 consists of a light-brown
sphalerite, which, over 9.27 metres, gives grades of 9.27 per cent zinc.
Values of 2.54 per cent, over 17.59 metres, and 3.64 per cent, over
12.15 metres, have also been recorded. In Boreholes UD32 and UD33, small
grains of galena and sphalerite, similar to that described in Borehole UD30,
were detected with minor chalcopyrite and pyrite. Most of the ore is
increased thickness of the chert-breccia, in Borehole UD30, deposited on the palaeokarst surface. In all the boreholes, the Malmani dolomite is unconformably overlain by the chert-breccia of the Fountains Formation, which is, in turn, covered by the black, carbonaceous mudstones and quartz arenites of the Timeball Hill Formation. Although several dolerite dykes and sills are present in the dolomites, none appears to have a close spatial relationship to the sulphides.

C. SEDIMENTOLOGY

There are abundant sedimentary cycles in the Intimately-Mixed Dolomite-and-Chert Zone and the prevailing sedimentary environment was shallow-marine. The presence of mottled dolomite horizons indicates the development of supratidal conditions, and textures indicative of replaced evaporites have been detected. In the area investigated, no distinct lateral facies changes were evident, and the syn-depositional tectonic activity does not appear to have drastically modified the palaeotopography. Coarse-grained dolomite zones were not generated, as in the Complex Dolomite Zone, and, consequently, groundwater refluxing was probably not a major process. Textures examined in thin-section show a fine-scale, inter-relationship between silica and dolomite. The silica invariably occupies the core of individual fenestrae, and this illustrates the gradual filling of an early porosity, however, there is no indication of distinctive fluid-migration paths, and, it is difficult to determine whether the dolomitization and silicification of the Intimately-Mixed Zone took place under mobile or static conditions.

D. MINERALIZATION

1. Introduction

The mineralization in Borehole UD30 consists of a light-brown sphalerite, which, over 9,27 metres, gives grades of 9,27 per cent zinc. Values of 2,54 per cent, over 17,59 metres, and 3,64 per cent, over 12,15 metres, have also been recorded. In Boreholes UD32 and UD33, small grains of galena and sphalerite, similar to that described in Borehole UD30, were detected with minor chalcopyrite and pyrite. Most of the ore is
concordant with bedding in the dolomites, but may be present in quartz veins, and is frequently brecciated. The sphalerite is invariably associated with silica, either in the form of quartz or chert.

During the course of this investigation abundant pyrite was often encountered in the various black, carbonaceous shales of the sequence, and, as gold had been detected in the argillaceous sediments of the Malmani dolomite (Minnitt et al. 1973), approximately 20 samples were submitted to the Western Deep Levels assay laboratories for gold and uranium analysis. The results are recorded in Table 9.

2. Nature of the ore

The sphalerite is occasionally coarsely crystalline, but is generally finely disseminated in silicified laminae, which lie parallel to the bedding, and these laminae, in many cases, form part of small domal stromatolites. Although euhedral crystals are not uncommon in the mineralized zone of Borehole UD30, the sphalerite typically displays extremely ragged crystal boundaries, enclosed in chert or quartz, and this gives the impression that both the ore and gangue silica crystallized synchronously. In the oolitic dolomicrite horizon at 624.62 metres, the sphalerite is situated between the ooids, and partially replaces them, which indicates that the ore occupies an early inter-granular porosity, and that emplacement was early-diagenetic. Where pyrite occurs in juxtaposition to sphalerite, no chemical interactions between the minerals were detected and it was often apparent that the pyrite had crystallized after the sphalerite. No chalcopyrite was detected in thin-section, but Boshoff (1977) reported that the chalcopyrite and galena within the ore-zone had crystallized after the sphalerite, although inclusion intergrowths, possibly exsolution phenomena, were described in the sphalerite grains.

3. Geochemistry of the ore and ore-zone

Major- and trace-element analyses for the samples in the ore zone are presented in Appendices 7 and 8. Only ten major-element analyses were carried out owing to the extremely high zinc contents of the samples, which
interfers with the detectors on the XRF machine. The average major-element composition of the dolomites in the ore-zone (Table 10) is not significantly different from the other dolomite types, except in the average silica values which are much higher. However, the trace-element geochemistry (Table 11) displays important differences, when compared with the typical composition of the Malmani dolomite, as shown in Table 11. The As, Mn, Mo and Na concentrations are normal, with Ag, Ba, and Ni slightly enriched, and, of great importance is the enrichment by many hundreds of times of Cd, Co, Cu, and Pb, with Zn obviously concentrated by many thousands of times. These metal ions probably partitioned in the sphalerite (ZnS) lattice, but are also finely disseminated, since it has not been possible to detect separate mineral phases with the microprobe in the sphalerite crystals. Several polished thin-sections of the sphalerite where probed for iron and manganese, but only negligible quantities were detected, and, this fact, together with the absence of zoning, indicates a low crystallization temperature (Williams, 1974). A sample of galena was also probed, but no trace elements were found.

### Table 10

AVERAGE MAJOR-ELEMENT COMPOSITIONS FOR THE INTIMATELY-MIXED DOLOMITE-AND-CHERT SAMPLES FROM THE MINERALIZED ZONE, BOREHOLE UD30

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>52.54</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.01</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.22</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.72</td>
</tr>
<tr>
<td>NiO</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>MnO</td>
<td>0.24</td>
</tr>
<tr>
<td>MgO</td>
<td>9.01</td>
</tr>
<tr>
<td>CaO</td>
<td>13.65</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.07</td>
</tr>
<tr>
<td>Na₂O</td>
<td>N.D.</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>S₂O₃</td>
<td>0.41</td>
</tr>
<tr>
<td>LOI</td>
<td>21.00</td>
</tr>
<tr>
<td>TOTAL</td>
<td>101.62</td>
</tr>
<tr>
<td>Moisture</td>
<td>0.08</td>
</tr>
<tr>
<td>CaO/MgO</td>
<td>1.59</td>
</tr>
</tbody>
</table>
108.
TABLE 11

AVERAGE TRACE-ELEMENT COMPOSITION FOR ORE SAMPLES WITH >1 PER CENT ZINC, FROM BOREHOLE UD30, COMPONED WITH THE AVERAGE MALMANI DOLomite COMPOSITION

<table>
<thead>
<tr>
<th></th>
<th>Average Ore sample</th>
<th></th>
<th>Average Malmani dolomite</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>1,4</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>As</td>
<td>&lt;100</td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>60</td>
<td></td>
<td>&lt;50</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td>300</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>143</td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>220</td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>?</td>
<td></td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Ga</td>
<td>?</td>
<td></td>
<td>&lt;1</td>
<td></td>
</tr>
<tr>
<td>Ge</td>
<td>Small</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>In</td>
<td>-</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>&lt;1000</td>
<td></td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>&lt;5</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Na</td>
<td>-</td>
<td></td>
<td>&lt;1</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>10</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>900</td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Sr</td>
<td>-</td>
<td></td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>-</td>
<td></td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>12,6%</td>
<td></td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

It was interesting to note that there is an increase in the zinc values upwards from the base of the shales of the Timeball Hill Formation, and that the shales are relatively enriched in Pb, Ni, and Ba. This suggests that there are some affinities between the shales and the zinc mineralization in Borehole UD30, UD32, and UD33. It is highly significant that, in the report made by Gallon (1980), an analysis of a carbonaceous mudstone from the Timeball Hill Formation showed the following base-metal values:

2000 ppm As, 550 ppm Co, 320 ppm Cu, 950 ppm Ni, 300 ppm Pb, 3700 ppm Zn, and 7,5 g/t Ag.
These figures tend to confirm the close affinity of the shales to the mineralization, although geochemical data from this study have shown that Cd, Co, and Cu are present in only small concentrations in the shales. The carbonaceous mudstone analyses presented in Table 9, show that uranium in the form $\text{U}_3\text{O}_8$ is normally present in trace amounts, and gold values average $<18 \text{ cm/g/t}$. Samples were taken from all parts of the stratigraphy and no preferential enrichment was seen.

4. Lead isotope data

Lead isotope compositions, and model lead ages, for galenas in the zinc deposit were determined by Professor Allsopp at the Geophysical Research Unit of the Bernard Price Institutes, at the University of the Witwatersrand in 1977. The results are shown in Table 12.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>$\text{Pb}^{208}/\text{Pb}^{204}$</th>
<th>$\text{Pb}^{207}/\text{Pb}^{204}$</th>
<th>$\text{Pb}^{206}/\text{Pb}^{204}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MY546</td>
<td>34.145 + 0.013</td>
<td>15.083 + 0.007</td>
<td>14.961 + 0.006</td>
</tr>
<tr>
<td>MY547</td>
<td>33.963 + 0.027</td>
<td>15.016 + 0.010</td>
<td>14.778 + 0.013</td>
</tr>
</tbody>
</table>

Model lead ages (b.y.)

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>$\text{Pb}^{208}/\text{Pb}^{204}$</th>
<th>$\text{Pb}^{207}/\text{Pb}^{204}$</th>
<th>$\text{Pb}^{206}/\text{Pb}^{204}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MY546</td>
<td>2.32</td>
<td>2.19</td>
<td>2.09</td>
</tr>
<tr>
<td>MY547</td>
<td>2.41</td>
<td>2.30</td>
<td>2.18</td>
</tr>
</tbody>
</table>

When the data are plotted on the two graphs in Figures 63 and 64, it can be seen that they plot very slightly outside the high density areas, and, it may be concluded, that they have undergone either a two-stage evolution process, or have been mixed with $\text{Pb}^{206}$-enriched ore-fluids. Model
ages suggest that the lead was derived from a $\approx 2.7$ b.y. source and that mineralization took place at $\approx 1.7$ b.y. It was pointed out by Allsopp (1978) that, as only two data points were available, errors in extrapolation could infer a $3.0$ b.y. source and mineralization $\approx 1.9$ b.y., which is a similar age to the Bushveld igneous activity. Five other data points have been presented in Figures 63 and 64, taken from the Zeerust lead-zinc ore field. These were collected by Gallon (1979) and are shown in Table 13.

**TABLE 13**

<table>
<thead>
<tr>
<th>Locali ty</th>
<th>$^{208}\text{Pb}/^{204}\text{Pb}$</th>
<th>$^{207}\text{Pb}/^{204}\text{Pb}$</th>
<th>$^{206}\text{Pb}/^{204}\text{Pb}$</th>
<th>Model ages (b.y.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bokkraal 344JP</td>
<td>34.72±0.17</td>
<td>15.28±0.08</td>
<td>15.03±0.09</td>
<td>1.98</td>
</tr>
<tr>
<td>Doornhoek 305JP</td>
<td>35.28</td>
<td>15.50</td>
<td>15.19</td>
<td>1.82</td>
</tr>
<tr>
<td>Kafferskraal 306JP</td>
<td>34.55±0.14</td>
<td>15.17±0.06</td>
<td>14.53±0.04</td>
<td>2.13</td>
</tr>
<tr>
<td>Strydfontein 326JP</td>
<td>34.97±0.28</td>
<td>15.38±0.12</td>
<td>14.72±0.12</td>
<td>2.0</td>
</tr>
<tr>
<td>Witkop 302JP</td>
<td>34.48±0.24</td>
<td>15.17±0.011</td>
<td>15.00±0.12</td>
<td>2.04</td>
</tr>
</tbody>
</table>

These data points plot on, and slightly above the primary growth curve and, when all the data, including UD30, is plotted on the trilinear diagram developed by Cannon et al. (1961), all the data clusters in the ordinary lead field, and slightly outside of the high probability zone (Figure 65). This indicates that these deposits are of questionable economic potential, and the overall production of lead and zinc from the mines in the Zeerust area is relatively small, although Doornhoek has produced 2 888 tonnes of lead ore. Both isotope values for the UD30 borehole plot close to the Zeerust data, but the model ages for mineralization indicate that the Western Deep Levels deposit may be somewhat younger. It is apparent from the very limited isotope data that the mineralization may have every chance of being economic, but a more detailed study of lead isotopes from the Transvaal is necessary for these deductions to be confirmed.
At this stage, several important statements should be emphasized when considering the zinc mineralization and its genesis:

(i) The host-rocks form the shallow, intertidal-to-subtidal facies of a sedimentary carbonate sequence and are bounded by two, possibly supratidal, mottled dolomite horizons. These dolomites display evidence of replaced evaporites, with a "chicken-wire" texture and length-slow chalcedony spherulites. During diagenesis and palaeo-solution activity, these
horizons represented a potential source of sulphate and, perhaps, chloride ions.

(ii) The sphalerite is stratiform and stratabound within the dolomites, and, in many cases, occupies the interparticle porosity developed between ooids and the inter-laminae pores of small domal stromatolites. This porosity was formed during sedimentation and diagenesis, and was subsequently infilled by silica, dolomicrite, and dolosparite. As the mineralization is closely related to the silica, it is concluded that, the ore emplacement was associated with at least one pulse of either diagenetic, or epigenetic silicification.

(iii) It is unlikely that sufficient metal ions could have been scavenged from the Malmanti dolomite by circulating basinal brines, since the ore-zone is enriched in Cd, Co, Cu, Pb, and Zn which are present in only minute quantities in the carbonates.

(iv) The absence of zoning in the sphalerites and the low iron content are indicative of low temperatures of formation.

(v) Isotope data suggest derivation of the associated galena either from a 3.0 - 2.7 b.y. source and mineralization between 1.9 and 1.7 b.y., or, mixing of lead-ore solutions with radiogenic leads from the surrounding, rocks. Economic potential of the deposit is implied by the plotting of the data close to areas of high probability on the trilinear diagram of Cannon et al. (1961).

F. SYNOPSIS

The zinc mineralization at Western Deep Levels Gold Mine has been regarded by A. Gallon, of the Anglo American Corporation of South Africa, as of Mississippi Valley-type, and, in many features it conforms to the classic geological concept of Mississippi Valley lead-zinc deposits. The most important similarities are:

(i) The mineralization is stratabound and situated within shallow, shelf, carbonate sediments of the Intimately-Mixed Dolomite-and-Chert Zone.
(ii) Although the deposit is frequently conformable with the bedding, quartz-veins and breccias are common, and discordant relationships are not unusual.

(iii) Silicification and dolomitization processes have significantly modified the carbonates.

(iv) In many cases, the mineralization has filled an original porosity.

(v) There are no contemporaneous volcanics associated with the sediments or the ore, but shales are abundant in the adjacent strata.

(vi) The tectonic setting is not complex, although a tectonic influence has been demonstrated, which has affected sedimentation of the host rocks and the development of the overlying palaeokarst topography.

(vii) The ore has a simple mineralogy.

(viii) Metamorphic grades are low.

(ix) Wall-rock alteration is absent, and the geochemistry indicates low-temperature, possibly hydrothermal, emplacement.

(x) Iron content of the sphalerites is low.

(xi) Hydrocarbons are present in the stratigraphy, although they do not appear to be directly associated with the ore.

The Western Deep Levels zinc mineralization is only significantly different to Mississippi Valley deposits in that J-type leads have not been detected.
G. GENESIS OF THE WESTERN DEEP LEVELS ZINC DEPOSIT

The zinc mineralization is hosted by the carbonates of the Malmani dolomite for several reasons. Firstly, porosity and permeability characteristics permitted unhindered movement and migration to the mineralization fluids, and, secondly, evaporite minerals supplied sulphate and chloride radicals to the ore-environment which functioned, not only as a transporting mechanism, but also as a precipitant of metal ions, as sulphides. Petrographic and geochemical evidence shows that the sphalerite is closely associated with silica, the solubility of which increases with increasing pH, and is most soluble at pH values greater than 9. In discussing the chemical aspects of metal-complexes, it has been shown in Chapter V, that bisulphide complexes, including ZnH$_2$S$_2$ and PbH$_2$S$_2$, are also more soluble at elevated pH, particularly in H$_2$S-saturated sodium chloride solutions (Hatoki, 1975). Chloride-complexes are relatively insoluble at high pH values, and, it is concluded that, the sphalerite mineralization at Western Deep Levels was probably transported as bisulphide-complexes under alkaline conditions, during silicification.

The geochemical investigation of the Malmani dolomite has shown that trace elements are generally present in only low concentrations, and, for this reason, the dolomites cannot be considered a source for the mineralization. This is further evidenced by the presence of Cd, Co, and Cu in the mineralized zone, which are insignificant components of the dolomites. Consequently, a model similar to that proposed by Davis (1977) for the Southeast Missouri lead deposits, where it is postulated that lead and zinc were extracted from sea water by algae and then reconstituted by connate brines during diagenesis, is not proposed for the Malmani dolomite. From the previous statements, it seems unlikely that the mineralization is genetically linked to the dolomites, but rather that the ore minerals were derived from an external source. However, as in most Mississippi Valley-type ore deposits, there is an important relationship between the carbonates and mineralization. It was noted by Beales (1975) that liquid petroleum is found equally in sandstone and limestone reservoirs, but that Mississippi Valley deposits are invariably only carbonate hosted. Consequently, it may be reasoned that features, such as lowering of temperature, dilution, and porosity, must play only a minor role in ore generation as these mechanisms work equally well in sandstones. The single most important
clue to the development of the mineralization at Western Deep Levels is the close spatial relationship to the mottled dolomite horizon. These relict evaporite zones do not confirm a sabkha or evaporative-reflux model, but suggest that the carbonates have acted as a host to the mineralization because they offered a ready supply of sulphate for the precipitation and transport of the metal ions.

The Western Deep Levels galenas are slightly enriched in $^{206}$Pb and the two isotope ratio data points (Figures 63 and 64) may be explained in three ways:

(i) The lead originated from within the mantle, where ordinary lead was mixed with uranium and thorium, and isotope compositions followed the natural evolutionary trend. This lead was mobilized during a pulse of mineralization, escaped upwards, and moved through the Witwatersrand Supergroup, incorporating minor $^{206}$Pb formed from $^{238}$U in the Witwatersrand sediment. This mechanism would be defined as a two-stage evolution model.

(ii) The second theory is that some ancient granitic basement was assimilated by a deep igneous magma. Lead was then expelled from this magma, which was slightly enriched in radiogenic lead, and was deposited in the Malmani dolomite. This mechanism is similar to that proposed by McKnight (1967), but no J-type or significantly-anomalous leads are found in the Transvaal. This could be explained by the fact that the mineralization in the Transvaal is much older than the Palaeozoic-rocks of the Mississippi Valley deposits, and the granitic source-rocks for the lead in the Transvaal had a much shorter evolutionary history; i.e. if the consolidation of the earth took place at about 4.5 b.y., then the maximum elapsed evolution time for the Transvaal granitic source would be approximately 2.0 b.y., but in the Mississippi Valley this could be up to 4.0 b.y., since mineralization is considered to have taken place at 150 m.y. Consequently less radiogenic lead could have formed by the Malmani dolomite times.

(iii) Finally, the leads may have been generated by a "mixing" process which could develop if the ore-bearing fluids were generated from the compaction and dehydration of sediments which were already contaminated by trace amounts of radiogenic lead, derived from the parent-rocks. This
process operated if the ore-minerals originated from the Timeball Hill Formation, in the case of the zinc mineralization in the Malmani dolomite.

The last mechanism is supported by much of the evidence at Western Deep Levels, but this can only be confirmed by detailed lead isotope data for both the dolomites and the overlying Timeball Hill Formation sediments. Many of the lead-zinc deposits in the Transvaal are situated in, or immediately below, the chert breccia of the Fountains Formation, and, on the basis of this, it is suggested that the ore-bearing fluids migrated out of the Timeball Hill Formation and down into the chert-breccia. This functioned as an aquifer through which the ore-bearing solutions were channelled and ultimately percolated into the underlying dolomites, depositing sulphides when the solutions encountered fluids enriched in sulphate, leached from evaporitic horizons.

The isopach map of the Fountains Formation (Figure 39), and the structure contour map of the base of the Fountains Formation (Figure 54), indicated contemporaneous tectonic control. In the vicinity of Borehole UD30, the chert breccia deposit thickens over a north-trending antiform, a feature which may have acted as a funnel into which the ore-solutions penetrated, and, in many ways, this mechanism is similar to that proposed for the development of Tsumeb and its related ore-bodies in South West Africa (Hughes pers. comm. 1980). If a hydrothermal origin is invoked, whereby the ore-solutions were derived from a deep igneous source, the presence of the Losberg intrusion, situated approximately ten kilometres south of Borehole UD30, near Fochville, is suggestive of a link with Bushveld igneous activity, and this hydrothermal mechanism cannot be discounted. However, it is strange that no other significant lead-zinc mineralization occurs in the lower part of the Malmani dolomite stratigraphy where numerous mottled zones have been identified. If the ore-solutions migrated upwards through the dolomite, it would be expected that, if the precipitating mechanism for the sulphides was directly related to sulphate derived from the mottled dolomites, other ore-zones would be developed.

It is difficult to evaluate the influence of hydrocarbons on the mineralization, particularly as these have been suggested as important in the development of the Mississippi Valley ores by Skinner (1967). However,