

**ECONOMIC GEOLOGY
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GEOCHEMISTRY OF THE MALMANI DOLOMITE
OF THE TRANSVAAL SUPERGROUP
IN THE NORTHEASTERN TRANSVAAL

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• INFORMATION CIRCULAR No. 97

UNIVERSITY OF THE WITWATERSRAND
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by

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ABSTRACT

Analysis of 152 specimens of carbonate from the Malmani Dolomite (circa 2 300 m.y. old) in a single stratigraphic profile through the formation has indicated the predominance of dolomite, with a near-theoretical CaO/MgO ratio. A gradual increase in CaO stratigraphically upwards is balanced by a diminution in MgO. Primary limestones, with low-MgO concentrations, are encountered in three major bodies near the top of the dolomite. Fe and Mn behave sympathetically through most of the dolomite, being concentrated in zones rich in clastic sediment. The correlation between Fe and Mn breaks down at the top of the formation, as the overlying iron formation is approached, and probably indicates a change towards more oxygenated conditions. The more highly oxidizing environment was possibly the consequence of a long period of activity of photosynthetic algae, represented by up to 1 700 metres of stromatolitic dolomite. It could also represent a sudden bloom of a photosynthetic organism. Both Pb and Zn are relatively enriched in the Malmani Dolomite, with respect to the average carbonate. Zn appears to be concentrated near the top of the dolomite. Pb is randomly distributed, except in the primary limestones, which are impoverished in the element. The Pb is thus thought to have been introduced into the carbonates during dolomitization.

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INTRODUCTION

The economic importance of the Malmani Dolomite has been stressed previously (Button, 1973a). It is the host to deposits of gold, lead, zinc, manganese, pyrite, fluorite, limestone, dolomite, and chrysotile asbestos. At present, the unit is being actively explored for stratiform lead-zinc deposits of the Mississippi Valley type. Exploration involves principally the analysis of stream-sediment samples for Pb and Zn. In order to interpret the geochemical results, a knowledge of background geochemistry in the dolomite is necessary. This compilation represents an attempt to provide further data which may be of use in mineral exploration.

PREVIOUS GEOCHEMICAL WORK IN THE MALMANI DOLOMITE

Horwood (1910) analysed two specimens of Transvaal Dolomite in his pioneer study of the geochemistry of Transvaal rocks. The one specimen was a dolomite with a CaO/MgO ratio close to the theoretical value. The second was a chertified carbonate in which the CaO was present in proportions appropriate to dolomite, but in which MgO was deficient, the deficiency being largely made up by SiO₂. He was of the opinion that silicification was secondary, at the expense of MgO, rather than CaO, and thought that the silica was originally present in the rock, was dissolved, and was locally re-distributed. He suggested that the dolomitization process "proceeded *pari passu* with the laying down of the formation".

Even though Horwood's (1910) analyses suggested a dolomite composition, in the Transvaal, the literature on the Malmani Dolomite invariably gives it as a "dolomitic limestone". This appears to stem from the analyses presented by Young (1906) from the Campbell Rand Dolomite in the northern Cape. Here, the CaO/MgO ratio certainly indicates a dolomitic limestone composition, in most cases. It is now known, however, that limestones are far more extensively developed in the northern Cape than in the Transvaal.

The first systematic study of the chemistry of the Malmani Dolomite was that of Eriksson (1971, 1972). In his study, a total of 85 dolomite samples (spaced from 13 to 17 metres apart through the stratigraphy) were analyzed for Ca, Mg, Fe, Mn, and Na. Some of Eriksson's results are, unfortunately, not directly comparable with those presented in this study, since they were done on the acid-soluble fraction. He found that the CaO/MgO ratios in the Malmani Dolomite varied very little (1,38 to 1,43) from the theoretical ratio for dolomite (1,39). The rocks analyzed were thus true dolomites in all but a few cases, and were not dolomitic limestones, a notion which had become entrenched in the literature. The acid-soluble Fe and Mn were found to behave sympathetically, being concentrated near the base of the unit and in a zone situated about 450 metres from the top of the 1 200-metre unit. Sodium was found to be concentrated near the base and top of the Malmani Dolomite. Zietsman (1964) made the statement, based on field observation, that dark dolomites probably owed their colour to a high MnO concentration. Eriksson's work confirmed this statement, showing that dark dolomites were rich in both iron and manganese.

The geochemical data presented here are essentially those drawn from Button (1973b). Further geochemical information has come from the dolomite to the north of Johannesburg (Truswell and Eriksson, 1975) and in the Boetsap area of the northwestern Cape (Eriksson and others, 1975). In the former area, 42 samples, spaced through the 1 452 metre-thick Malmani Dolomite were analyzed for Ca, Mg, Fe, and Mn. Once again, samples were shown to be dolomites. Sympathetic iron and manganese enrichments were encountered near the base of the dolomite, and in a unit extending from 400 to 560 metres from the top of the Malmani Dolomite.

COLLECTION AND PREPARATION OF SAMPLES

The samples analyzed in this paper were collected from the Malmani Dolomite in the north-eastern Transvaal, near the Penge asbestos mine (Figure 1). The collection of samples was subject

to a number of limiting factors. In the first instance, the entire dolomite stratigraphy had to be represented. In the second case, areas of strong folding and of metamorphism had to be avoided, as far as was possible. The area south of Penge represented a compromise, the entire formation being admirably exposed in the gorge adjacent to the Olifants River. The area is structurally simple, and metamorphism has only slightly affected the uppermost portion of the Malmani Dolomite.

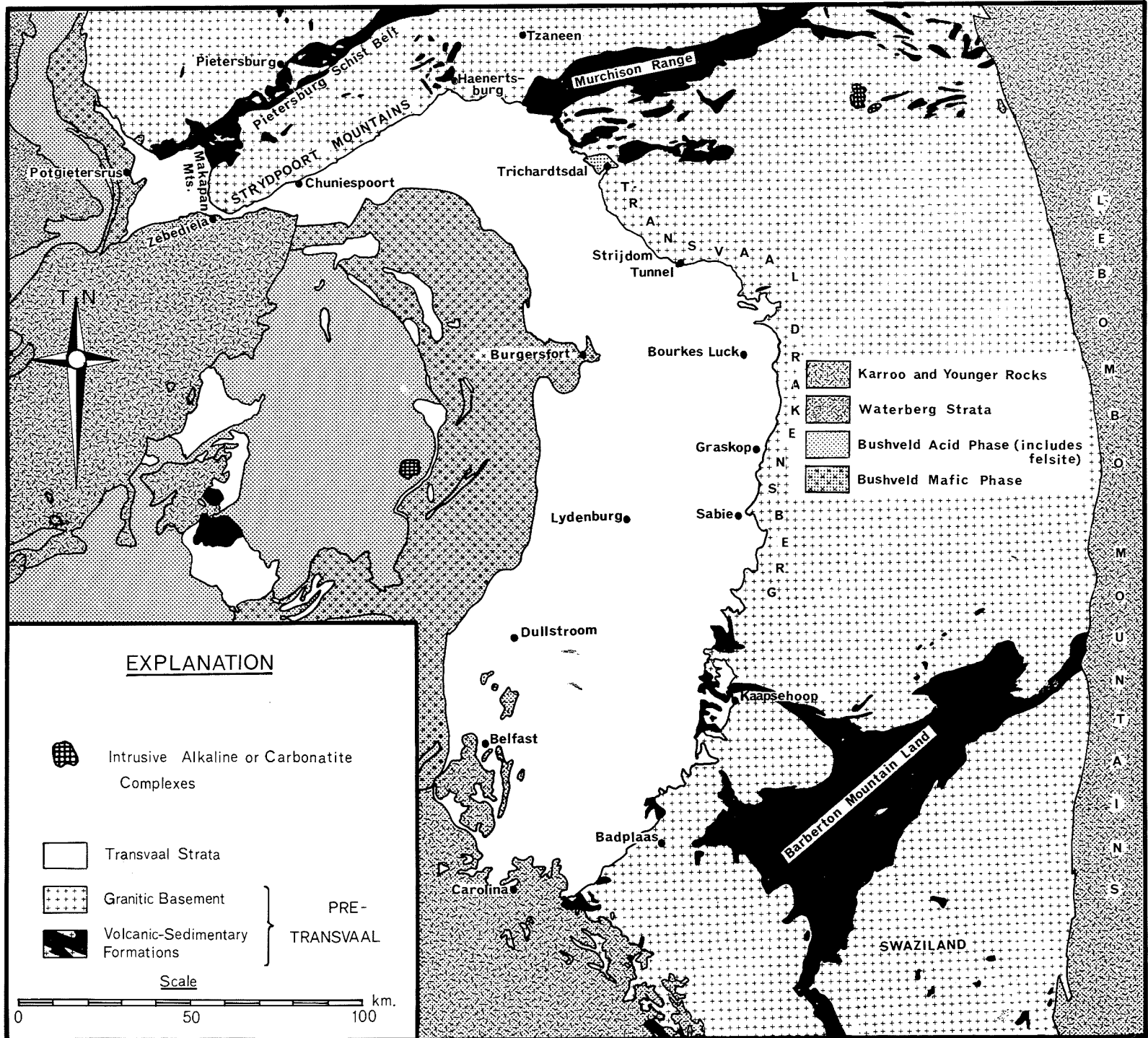


Figure 1 : General geology and location of traverse sampled.

The procedure adopted in the field was to traverse the dolomite stratigraphy up one of the steep spurs adjacent to the Olifants River. Thickness-control was provided by a Jacob staff with clinometer, set to the angle of dip of the strata. The stratigraphy was traversed, thicknesses and sample-positions were recorded, and descriptions of the geology made. In all but a few cases, samples were taken at regular, 5 Jacob-staff-length intervals (equivalent to a stratigraphic distance between samples of nine metres). A total of 153 samples was collected from the traverse.

On the traverse, hand-specimen-sized samples were selected, care being taken to select only fresh material, essentially free from visible chert. Subsequently, the samples were cleaned, and then crushed in a jaw-crusher. The crushed chips were screened, washed, dried, and sorted, only totally fresh fragments being selected. A number of semi-quantitative parameters were then measured on the cleaned rock chips. Colour was recorded, using a rock-colour chart. Reaction with dilute HCl was observed, and rated from 0 (very weak) to 3 (strong effervescence). The presence of any macroscopically visible chert was noted, and was rated from 1 (absent) to 3 (present in minor quantities). The selected chips were then pulverized and submitted for analysis. Analyses were performed by X-ray fluorescence on pressed pellets, in the National Physical Research Laboratory, Pretoria.

ELEMENTS ANALYZED

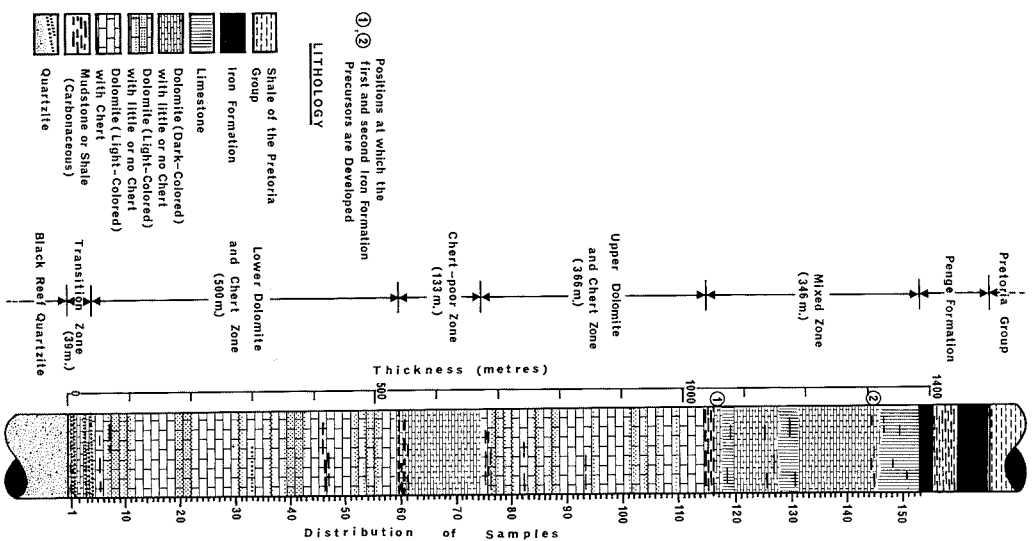
The carbonates of the Malmani Dolomite consist essentially of the minerals calcite (CaCO_3) and dolomite ($\text{CaCO}_3 \cdot \text{MgCO}_3$). Varying amounts of iron and manganese are present in the carbonate lattices, as well as in other minerals. Secondary replacement of carbonates by silica (in the form of chert or quartz blebs) is a common feature. Although samples were chosen so as to be essentially free of macroscopic chert, it was impossible, in practice, to eliminate this phase entirely. It was thought that the major-element chemistry would be satisfactorily accounted for by the elements Ca, Mg, Fe, Mn, and Si. These were determined analytically, the results being expressed as a percentage by weight of CaO , MgO , Fe_2O_3 , MnO , and SiO_2 .

From a trace-element point-of-view, it was decided to determine the Pb and Zn concentrations in the dolomite. In view of the almost universal association of lead and zinc deposits with carbonate sediments, any coherent trends in these elements through the formation could be useful in the search for payable deposits in the Malmani Dolomite. Such results are also essential to the interpretation of stream-sediment geochemical sampling.

STRATIGRAPHY OF THE MALMANI DOLOMITE

The stratigraphy and stratigraphic relations in the Malmani Dolomite of the eastern Transvaal have been described by Button (1973a). Only a generalized outline is given here. In the Penge area, the Malmani Dolomite rests on the Black Reef Quartzite, and is overlain by the banded iron formation of the Penge Formation (Figure 2, left hand side). It has a total thickness of 1 384 metres, and is subdivided into five major stratigraphic units. The *transition zone* (39 metres) comprises dark-coloured, chert-free dolomite, with lenses of quartzite and carbonaceous shale. It grades up to the *lower dolomite and chert zone*, 500 metres thick, and comprising lighter-coloured dolomite and chert, with only minor clastic sediment in the form of carbonaceous shale. The *lower dolomite and chert zone* is overlain by the *chert-poor zone* (133 metres). This commences with a veneer of chert breccia, followed by dark-coloured, chert-free dolomite, with abundant carbonaceous shale layers at the base, and grades upwards to the *upper dolomite and chert zone* (366 metres). The uppermost major unit of the dolomite is known as the *mixed zone*, and is 346 metres thick in the Penge area. It commences at the base with a veneer of chert breccia, overlain by carbonaceous shale. The main body of the unit comprises dolomite (dark-coloured, relatively chert-free) and primary limestone. The uppermost limestone is dolomitized at the contact with the overlying iron formation. The contact is a gradational one, involving layers of iron-rich dolomite, chert, and iron silicate (principally grunerite).

The uppermost units of the Malmani Dolomite are weakly influenced by the metamorphic aureole of the Bushveld Complex in the Penge area. The most obvious effects are the crystallization, in iron-rich dolomites, of numerous flakes of a chloritic mica.



Malmmani Dolomite – Variation of Chemical and Physical Parameters through the Stratigraphy

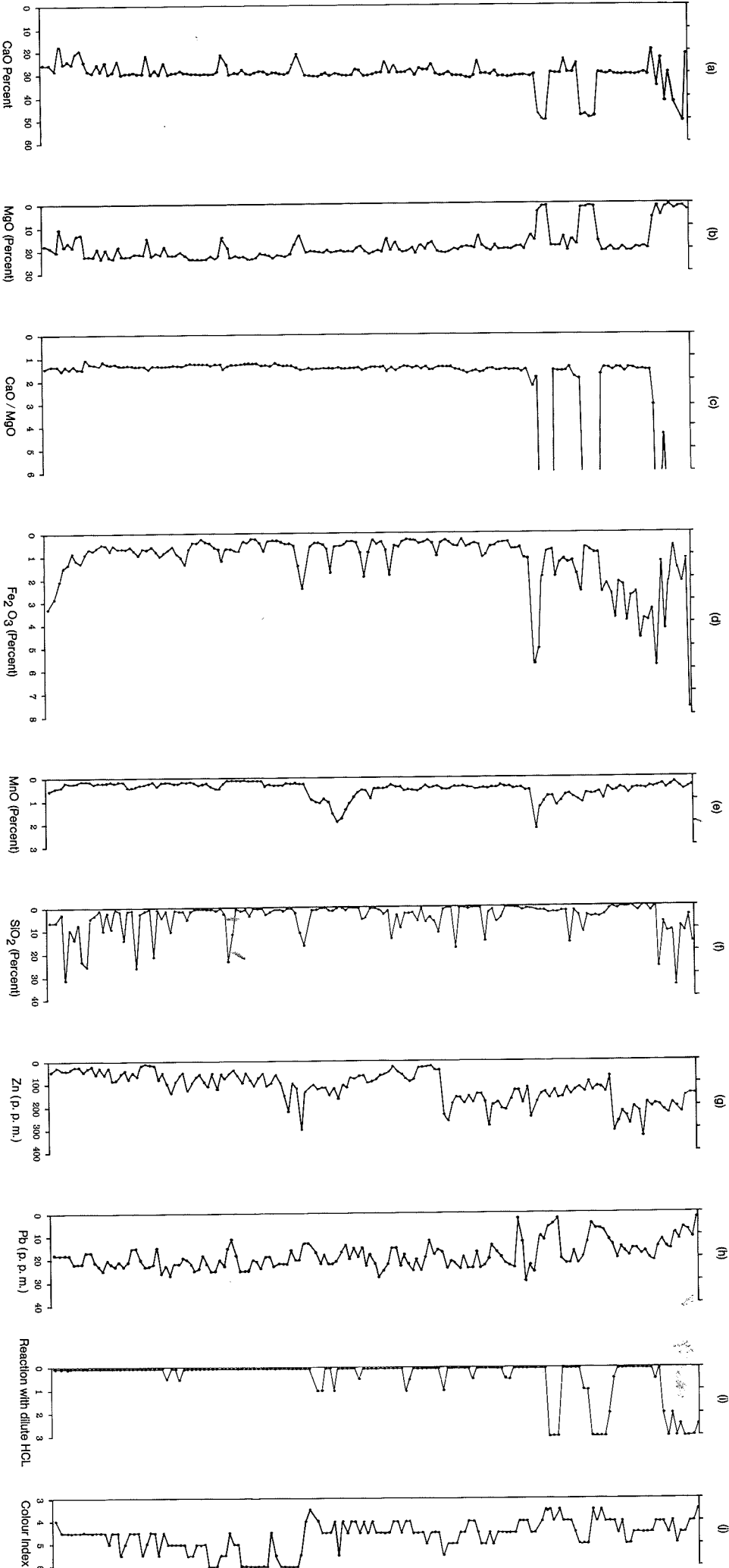


Figure 2 : Variation of chemical and physical parameters through the stratigraphy of the Malmmani Dolomite.

RESULTS OF ANALYSES

(a) CaO

A histogram for CaO values is shown in Figure 3. The distribution is essentially a normal one, with the modal class from 20 to 30 percent. The mean CaO value was calculated at 30,0 percent, from which the standard deviation is 5,5 percent. The mean value corresponds almost exactly with the theoretical concentration of that oxide in pure dolomite (30,4 percent). The correspondence is due, in the first instance, to most of the specimens being close to true dolomite in composition. Secondly, those rocks containing more CaO than dolomite (the limestones in the Malmani) were offset by those containing less CaO than dolomite (principally the chert-bearing dolomites). Cousin's (1973) composite Malmani Dolomite sample contained 27,03 percent CaO. The higher value for the eastern Transvaal is due to the presence of primary limestones in that area.

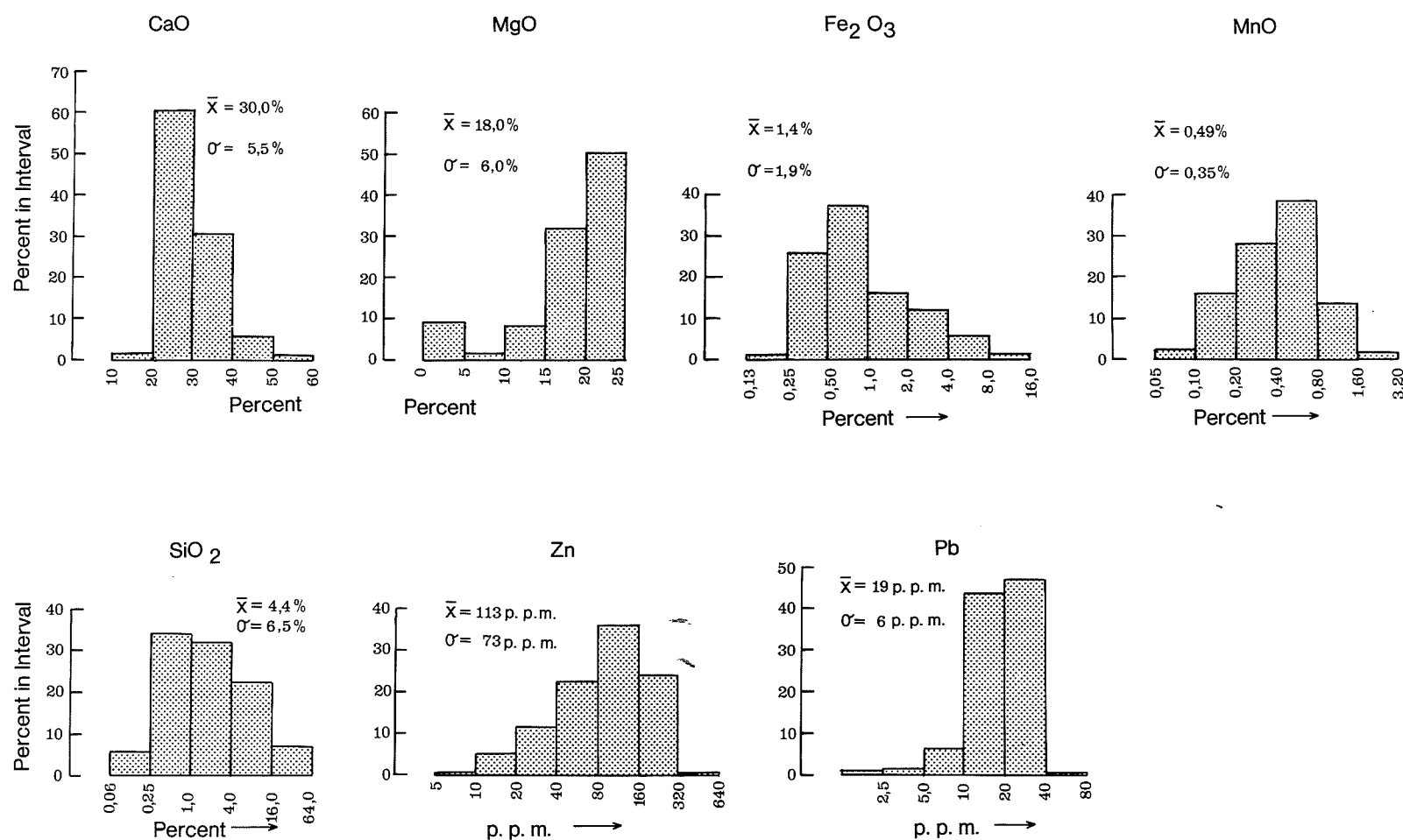


Figure 3 : Histograms of chemical parameters of the Malmani Dolomite.

The stratigraphic distribution of CaO is instructive (Figure 2). There is a broad plateau of values at about the 30 percent mark. Upwards through the column, the plateau-height rises gradually, so that the background concentration of CaO in the carbonates rises subtly from 29 to 31 percent. Superimposed on the 30 percent CaO plateau are a number of negative deviations, the CaO content dropping to 20 percent in places. These negative deviations, which are particularly common in the Malmani below the mixed zone, are in each case mirrored by a similar deviation in the MgO curve (Figure 2). In effect, those samples deficient in CaO tend to contain less MgO as well. The reason for this is readily apparent when studying the SiO₂ curve (Figure 2). Each negative peak of CaO and MgO coincides with a positive peak in SiO₂. This could be caused either by chertification or by the presence of silica-bearing minerals (such as detrital quartz grains or clay minerals). Both field observations and arguments to be developed below suggest that most of

the SiO_2 peaks are due to chertification of dolomite, the SiO_2 making up the shortage of CaO and MgO .

Positive deviations from the 30-percent plateau are also present in the CaO distribution curve. These are restricted to the mixed zone, and correspond exactly to the limestones observed in the measured profile. CaO values up to, and sometimes slightly exceeding, 50 percent are present (for purposes of comparison, pure limestone carries just over 56 percent CaO). The two lower limestone bodies represent a fairly pure rock, of the sort that might be suitable for the manufacture of cement. The uppermost limestone body, although much thicker, contains erratic CaO proportions, the balance being made up largely by SiO_2 (Figure 2).

(b) MgO

The Malmani Dolomite contains an average amount of 18,0 percent MgO , from which the standard deviation is 6,0 percent. The histogram for MgO distribution is shown in Figure 3. It is a very strongly negatively-skewed distribution. The reason for the latter feature is quite obvious when scanning the data on the MgO distribution plot (Figure 2). While MgO concentrations in the 20-percent range are very common, no samples exceed this value by more than a few percent, while a great number of samples contain less MgO (in the range down to 1 or 2 percent). The principal mode of the distribution is 20-25 percent, and reflects the 21,9 percent of MgO in pure dolomite. The secondary mode (0-5 percent) is due to the small number of fairly pure limestones in the Malmani Dolomite. The formation contains, on average, nearly 4 percent less MgO than the figure for true dolomite. This is due, in the first instance, to the chertification of dolomite, secondly, to the preservation of some primary limestone, and, thirdly, to substitution of Mg by Fe and Mn . All three factors tend to decrease the proportion of MgO in the Malmani Dolomite. The 18,0 percent average for the eastern Transvaal coincides closely with Cousins's (1973) composite dolomite specimen, which carries 17,78 percent MgO .

The distribution of MgO through the stratigraphy is shown in Figure 2. In the profile, an MgO plateau is evident, the complement of the CaO plateau in Figure 2. An important factor is the gradual decrease of average MgO content upwards in the stratigraphy. Near the base, the plateau stands at around 23 percent MgO ; at the top it stands at 20 percent MgO . It is evident that the trends of the CaO and MgO plateaus are antipathetic, the CaO increasing gradually upwards, the MgO decreasing in that direction.

In contrast to the CaO plateau, the MgO plateau shows only negative deviations. As pointed out above, the small negative deviations are due to the replacement of dolomite by chert. This is borne out by the smooth nature of the MgO curve in the chert-free sections of the mixed zone and in the chert-poor zone. The larger negative deviations (MgO in the 1-to-2-percent range) coincide with the limestone layers. The uppermost limestone, though carrying erratic CaO values, is typified by consistently low MgO concentrations.

(c) CaO/MgO

The CaO/MgO ratio effectively eliminates the disturbances of the MgO and CaO curves brought about by chertification, and results in a much smoother curve. The first-order trends in the plateaus of MgO and CaO are confirmed by the gradual, but very distinct, upward increase in the CaO/MgO ratio. Thus, the plateau at the base of the formation typically stands at around 1,3, while near the top, the ratios are usually 1,6. It is apparent that the average carbonate near the base is a little more magnesian than the pure dolomite (where the ratio is 1,39), while the average sediment at the top is a bit on the calcic side of dolomite.

Other interesting features are the small, but very distinct, positive bumps in the CaO/MgO curve, which coincide with heavily-chertified dolomite (SiO_2 positive peak combined with negative peaks of CaO and MgO). The curves would suggest that, where a specimen has been chertified, the CaO/MgO ratio increases slightly. This implies that, during the chertification process, the dolomite loses proportionally more MgO than CaO , a feature suggested by Horwood (1910) on the basis of an analysis of one sample.

(d) Fe_2O_3

The iron present in the Malmani Dolomite is expressed as a percentage by weight of Fe_2O_3 . This does not imply that the iron in the specimens is in the ferric state. To the contrary,

a large proportion of the iron is probably found in the ferrous state, where it substitutes for the Ca^{2+} and Mg^{2+} cations in the dolomite lattices. The histogram for Fe_2O_3 was found to be gently skewed in a positive sense, when plotted on a logarithmic scale (Figure 3). The population is thus probably of a log-normal type. The mean Fe_2O_3 content of 157 specimens was found to be 1,41 percent, from which the standard deviation is 1,87 percent.

The pattern of iron distribution through the Malmani Dolomite is shown in Figure 2. This chart is of first-order importance in speculating on the origin of the iron formation in the overlying unit. The iron distribution pattern and its bearing on the genesis of this rock-type have been discussed elsewhere (Button, 1974). The most obvious change is the trend to higher iron concentrations upwards in the stratigraphic column. The trend is not a smooth one, but is cyclical in nature. Upwards in the column, both peaks and hollows increase in iron concentration. A second feature is that the basal rocks of the three transgressive megacycles (see Button, 1973a) are particularly rich in iron. The transition zone carries up to 3,30 percent Fe_2O_3 ; the base of the chert-poor zone carries up to 2,41 percent; and the basal dolomite of the mixed zone carries 5,73 percent. The cyclical pattern sketched out on the basis of geological parameters is mirrored by the geochemical pattern in iron. A third point worthy of note is the small amount of iron (relatively speaking) in the primary limestones of the mixed zone. All three limestone bodies show up as negative features in the iron-distribution pattern of Figure 2.

(e) MnO

The average carbonate of the Malmani Dolomite contains 0,49 percent MnO. The standard deviation is 0,35 percent. The histogram for MnO is shown in Figure 3, and appears to be of a log-normal type. Cousins's (1973) composite sample of the Malmani Dolomite contained 0,47 percent MnO.

The distribution pattern for MnO through the profile (shown in Figure 2) bears many resemblances to the Fe_2O_3 pattern. In the first instance, the MnO background increases upwards in sympathy with Fe_2O_3 . In the lower dolomite and chert unit, the background is around 0,20 percent MnO; in the upper dolomite and chert unit, it is about 0,40 to 0,50 percent; and in the mixed zone it is about 0,50 to 0,60 percent. Manganese shows a cyclical pattern in sympathy with the one outlined both by the geological features and by iron. The base of each transgressive cycle is enriched in the element. In the basal transition zone, up to 0,55 percent MnO is present (as against the 0,20 percent background). In the chert-poor zone, values are generally high, and one specimen contained 1,92 percent MnO. The base of the mixed zone contained more MnO than any other specimen in the Malmani Dolomite of the Penge area (2,23 percent). Upwards in the mixed zone, the sympathetic behaviour between MnO and Fe_2O_3 ceases to exist, the former decreasing gradually but persistently, as the Penge Formation is approached.

Primary limestone appears to be depleted in manganese. The two lower limestone bodies show up as weak but distinct troughs in the MnO distribution pattern of Figure 2.

(f) SiO_2

The Malmani carbonates contain SiO_2 in diverse forms. Most commonly, it is present in the form of chert which replaces the carbonates. It is also present (though to a lesser extent) in detrital quartz grains, in the clay minerals of argillaceous carbonates, in secondary quartz blebs, and in the minor metamorphic silicates. It is thus not surprising that the SiO_2 distribution through the stratigraphy is highly irregular, ranging from 0,16 to 31,3 percent. A histogram of SiO_2 values is shown on this diagram. The modal class is 0,25 to 1,0 percent, while the average is 4,2 percent. The standard deviation was calculated at 6,4 percent.

The stratigraphic distribution of SiO_2 is shown in Figure 2. The pattern is a highly erratic one. It does, however, show some system. The lower and upper dolomite and chert zones are very variable, a feature probably reflecting the random nature of the chertification process. The transition zone contains low but variable amounts of SiO_2 , except for one specimen (Number 4) which carried detrital quartz grains. The basal dolomites of the chert-poor zone (Numbers 60 and 61) contain fairly high proportions of SiO_2 , due probably to their association with numerous shaly beds. The main portion of the chert-poor zone is characterized by a uniformly low proportion of silica. The peaks in the lower half of the mixed zone could not be related to any geological parameters seen in the field, while those at the top of the mixed zone relate to the minor development of chert, to the presence of small amounts of metamorphic silicates, and to the clay minerals in shales associated with the limestones.

(g) Zn

A histogram for Zn, with logarithmic intervals, is shown in Figure 3. The mean value is 113 ppm, the range being from 11 to 335 ppm. The standard deviation from the mean was calculated at 73 ppm. The Malmani carbonates appear to be highly anomalous with regard to Zn; they contain nearly 6 times more of the element than the average carbonate of Turekian and Wedepohl (1961), who quoted a figure of 20 ppm. They are closer to the average shale, which carries 95 ppm. The highest value (335 ppm) is nearly 17 times richer in Zn than Turekian's and Wedepohl's average carbonate.

The Zn has a well-defined pattern of distribution through the stratigraphy (Figure 2). In the first instance, it shows a gradual but distinct upward increase on average, values in excess of 200 ppm being absent in the transition zone and very rare in the lower dolomite and chert zone. A second, and important, feature are the peaks found immediately above and below the two intra-formational unconformities of the Malmani Dolomite. According to Callahan (1966), most of the Pb-Zn orebodies of the Tri-State region, United States, are found immediately below, on, or immediately above such sedimentational hiatuses. Other peaks are not as easily explained. Those associated with specimens Nos. 94, 95, and 105 (in the upper dolomite and chert unit) and with Nos. 134 through 150 (in the mixed zone) have no ready explanation.

(h) Pb

The Pb concentration in the Malmani Dolomite ranges from 60 to less than 5 ppm, the average having been calculated at 19 ppm. The standard deviation from the mean is relatively small (6 ppm). The histogram for Pb, plotted on a logarithmic scale, is shown in Figure 3. Only one sample exceeded 30 ppm; this was a ferruginous dolomite from the mixed zone.

The distribution of Pb through the stratigraphy is extremely erratic; it appears as if it varies more-or-less randomly about the mean, with little regard to stratigraphic control. The only geologically significant variations in the Pb content appear to be in the primary limestones of the mixed zone, which are strongly depleted in the element. This suggests that most of the Pb in the Malmani was introduced during the dolomitization process.

The average carbonate is said to carry about 9 ppm of Pb (Turekian and Wedepohl, 1961). By contrast, the Malmani Dolomite carries, on average, 19 ppm of the element. This figure compares to the amount of Pb in the average shale, which is 20 ppm according to Turekian and Wedepohl (1961).

(i) Reaction with Dilute Hydrochloric Acid

The reaction of carbonate specimens with dilute hydrochloric acid is charted in Figure 2. The reactions were rated from 0 (very weak) to 3 (very strong). The curve shows three prominent peaks in the mixed zone, which coincide with the high CaO-low MgO peaks of the curves in Figure 2. It was thus evident that acid-testing of rock-chips was a reliable method of identifying low-magnesian, high-calcium carbonates. The small peaks in the 0-1 range appear to be spurious, representing operator error in this semi-quantitative test.

(j) Colour Index

Nearly all the carbonates of the Malmani Dolomite range in colour from light to dark grey, and very seldom show variations in other hues. Consequently, the value (or lightness) index, which ranges from N9 (white) to N1 (black) was a convenient way of expressing the colour of the Malmani carbonates. For this purpose, the rock-colour chart (Goddard, 1951) was ideally suited. In the Malmani Dolomite, carbonates range from light grey (N6), through medium grey, medium dark grey, to dark grey (N3).

The distribution of these values through the Malmani Dolomite is shown in Figure 2. The pattern, although fairly erratic, does have some system to it. The iron- and manganese-rich dolomite of the transition zone at the base of the Malmani strata is relatively dark. Upwards through the lower dolomite and chert zone, colours become lighter, on average, and are lightest just beneath the middle chert-poor zone. The base of the chert-poor zone is marked by very sudden darkening of dolomite, again in a zone rich in iron and manganese. The upper dolomite and chert zone is, on average, darker than the lower dolomite and chert unit. The dolomites at the base of the mixed zone (rich in iron and manganese) are dark-coloured. The mixed zone, as a whole, is the darkest of the units in the Malmani Dolomite. If curves (i) and (j) of Figure 2 are compared,

there appears to be a correspondence of limestones in the mixed zone with darker-than-average colours, the replacing dolomite being slightly lighter-coloured.

DISCUSSION OF GEOCHEMICAL RESULTS

The geochemical study of the Malmani Dolomite has shown that the predominant carbonate type is a dolomite with a near theoretical ratio of CaO to MgO. This confirms the findings of Eriksson (1971), who showed that the Malmani carbonates, at least in the Transvaal, are true dolomites and are not dolomitic limestones.

Plots of CaO and MgO through the stratigraphy outline complementary CaO and MgO plateaus. Stratigraphically upwards, the plateau rises gradually, in the case of CaO, and becomes lower in the case of MgO. This effect is clearly seen in the plot of the CaO/MgO ratio, which rises gradually but steadily through the formation. This is a feature of first-order importance, and is thought to be due to the multi-stage nature of the dolomitization process. Dolomitization often takes place penecontemporaneously by the fluxing of soft sediment by high-pH brines with relatively high Mg/Ca ratios (Deffeyes and others, 1965). This process is thought to have operated more-or-less continuously during Malmani times, and older sediments can be expected to have been through the dolomitization cycle more times than younger ones. Such an explanation would account for the rise in the CaO/MgO ratio through the column, as well as for the fact that primary limestones tend to be preserved in the upper portions of the formation.

The field study brought to light fairly extensive bodies of primary limestones not previously documented in the Transvaal. Chemically, these were shown to be low-magnesian limestones of a type possibly suited to cement manufacture. The limestones (especially the uppermost and thickest one) contain variable (sometimes large) proportions of SiO₂. Careful fieldwork could possibly reveal low-SiO₂ limestones in sufficiently large quantities to be exploited for the cement industry.

The CaO/MgO plot reveals another interesting feature. In samples containing much SiO₂ (chert-bearing dolomite), a slight rise in the ratio is discernible. It is concluded that, during the chertification process, MgO was replaced preferentially to CaO.

The mineralogical form taken by the Fe and Mn was not investigated in detail. Some of the iron is undoubtedly present in pyrite, a few specks of which are found in some specimens. The bulk of these elements is, however, almost certainly sited in the carbonate lattice. This is suggested by the weathering of the Fe- and Mn-rich dolomites, which develop uniform chocolate-brown surfaces, there being no suggestion of local concentrations of the elements. Secondly, the staining of fresh faces of iron-rich dolomite with potassium-ferricyanide results in an even blue colour. The latter confirms that much of the iron is present in the ferrous state, and is thus suited to replacement of Mg²⁺ in a dolomite lattice. Thirdly, if both Fe and Mn substitute for Mg²⁺ in dolomite, this effect should be discernible in the concentration of MgO in a dolomite rich in the former elements. This is clearly seen in a number of cases, the most obvious being the dolomite at the base of the mixed zone. This rock, which contains 5,1 percent Fe₂O₃ and 2,2 percent MnO, has an MgO content of only 13,8 percent (in contrast to the 21,9 percent needed for pure dolomite). The CaO concentration remains stable at 31,1 percent in this specimen, just above the theoretical value for dolomite (30,4 percent). The substitution of Fe and Mn for Mg is also observable in the CaO/MgO plot, which, for the sample under discussion, is 2,25 (versus 1,39 for pure dolomite). There is thus very strong evidence that the bulk of the Fe and Mn in the Malmani Dolomite is present as Fe²⁺ and Mn²⁺ cations, which isomorphously substitute for Mg²⁺ in the dolomite lattice. This supposition is supported by the electron microprobe study of Eriksson and others (1975) who found that iron and manganese are concentrated in the dolomite crystals in carbonates containing both dolomite and calcite.

The sympathetic behaviour of Fe and Mn through the bulk of the Malmani column has been demonstrated. This sympathetic relationship has been previously documented in the Malmani carbonates (Eriksson, 1971). In the literature of the chemistry of carbonates, this association appears to be almost universal (Graf, 1960; Veizer and Demovic, 1973). According to these authors, in addition to being correlated one to the other, Fe and Mn tend to have a strong relation with the amount of insoluble residue (particularly clay minerals) in a carbonate. This latter association is almost

certainly present in the Malmani Dolomite. Although the proportion of clay in the specimens was not studied, the correlation of Fe- and Mn-rich carbonates with zones containing high proportions of clastic sediment (quartzite and mudstone) strongly favours such a relation. This correlation suggests that the Fe and Mn were introduced into the basin along with the shaly and quartzitic detritus. Thus, pulses of clastic sedimentation in the carbonate-precipitating Malmani Sea were coincident with periods of Fe- and Mn-rich dolomite formation.

The iron cycles in the upper part of the mixed zone are not mirrored by manganese. This lack of correlation, as the Penge iron formation is approached, is a phenomenon of first-order importance. One of the most definitive statements on the behaviour of iron and manganese in the sedimentary environment is that of Lepp (1963). Under chemically inert conditions (mildly oxidizing or reducing), the Mn^{2+} and Fe^{2+} cations are said to behave similarly, and to precipitate together as carbonates. Lepp supports an earlier conclusion that the solubilities of iron and manganese carbonates are very similar; in addition, their carbonates have overlapping stability fields; under these conditions, there is no reason for the two metals to separate; to the contrary, there are good reasons why they should be intimately associated. Using the arguments developed above, it could be reasoned that, if Fe and Mn behave sympathetically, a weakly oxidizing or reducing condition can be inferred. The carbonates in the main body of the Malmani show such a correlation, and are thus inferred to have been deposited under such conditions.

The Fe-Mn relation breaks down in the upper phase of the mixed zone, as the iron formation is approached. The geochemical separation of Fe and Mn suggests the onset of more oxidizing conditions. Under such circumstances, iron is much less soluble at any given pH than manganese (Lepp, 1963). The Eh-pH relations for Mn and Fe in the presence of CO_2 have been described by Hem (1972). According to his diagrams, the carbonates of Fe and Mn co-exist in mildly reducing conditions under a neutral to slightly alkaline pH. Separation of the elements can be effected by an increase in Eh (more oxidizing conditions) or changes in pH. Hem's diagrams were constructed for systems free of Mg and Ca. It is not known to what extent the presence of these elements would modify the Eh-pH relations. The suggestion that the separation of Fe and Mn was caused by an increase in degree of oxygenation of the sedimentary environment is, however, not ruled out on the basis of the Eh-pH diagrams. It is argued that the first shelf-carbonate sedimentation probably saw the start of local build-ups of oxygen, the gas being liberated by widespread sheets of photosynthetic algae. A critical oxygen content in the waters of the Malmani sea is thought to have been built up towards the end of the depositional era of the Malmani Dolomite. Such a change would account for the geochemical separation of Fe and Mn towards the end of dolomite times. It would also explain the onset of iron formation precipitation. Iron formation, with its mixed ferrous-ferric mineral species (such as magnetite), requires at least a modest amount of oxygen in the basinal waters.

A final feature of Fe and Mn distributions is the inference that, during dolomitization, brines rich in Mg, Fe, and Mn acted on primary limestones to form dolomites with varying amounts of Fe and Mn. The concentration of the latter elements was thought to have been due, firstly, to their influx along with clastic sediments and, secondly, to their evaporative concentration within a restricted basin.

The distribution pattern of the trace elements through the dolomite is more difficult to explain. The pattern for Zn suggests an overall increase upwards through the formation. Local concentrations are present adjacent to the two known intraformational unconformities. Other anomalies can be related to no obvious geological causes.

With regard to Pb, Jones and Hirst (1972) found that this element tended to be related to clay minerals in the carbonate rocks. This confirmed Graf's (1960) statement that Pb was associated with the insoluble fraction in carbonates. If such were the case in the Malmani Dolomite, Pb peaks would be expected in the clastic-rich phases of the formation. No such peaks are present, so that concentration of Pb with the insoluble fraction was evidently not a factor of importance in the Malmani Dolomite.

Roberts (1973) presented a theory to account for the Woodcutters Pb-Zn prospect in the Northern Territory of Australia. His scheme involved, as a first step, the evaporative concentrations of Pb (and Zn) in the waters of a partially-restricted basin. At a later stage, primary carbonates (Mg-calcite or aragonite) were precipitated, the Pb and Zn being fixed in the lattices of these minerals. Subsequently, during dolomitization of the primary carbonates, re-structuring or re-ordering of the crystal lattices was inferred to have resulted in the expulsion of Pb and Zn cations. The latter were released to pore solutions, where they were rendered stable by complexing with organic materials. During deformation, he argued, the pregnant solutions were moved to fractures

where they deposited their load. Roberts' theory does not appear to apply to the Malmani Dolomite. The opposite situation, in fact, applies. The primary carbonates appear to have been able to tolerate only relatively small amounts of Pb, this element being concentrated preferentially in the secondary dolomite. In the case of the Malmani Dolomite, the Pb must have been concentrated (by evaporation) along with Mg. Fluxing by the heavy Mg-rich brine (which caused dolomitization) also resulted in the addition of Pb to the newly-formed carbonate.

POSSIBLE VENUES FOR Pb-Zn MINERALIZATION IN THE MALMANI DOLOMITE

The origin of the mineralizing fluids in Mississippi Valley-type Pb-Zn deposits is still a debatable topic. There appears to be agreement, however, on one of the major controls on mineralization, namely, that of porosity-permeability. Most exploitable deposits are found in situations of relatively high paleo-porosity and -permeability. These properties can be enhanced through the agency of depositional, or post-depositional, processes. Under the first heading would be the sedimentary breccias and oölitic rocks in the Malmani Dolomite, which, prior to cementation, must have been very porous and permeable. Included under the second heading would be zones of enhanced porosity and permeability in ancient cave-fill breccias along unconformities, and in zones of intense fracturing and jointing. Any logical approach to prospecting for Pb and Zn in the Malmani Dolomite should take into account these two factors.

Firstly, a detailed stratigraphic compilation should be attempted, which would indicate the position of porous and permeable sediments, and would locate unconformities along which cave-fill breccias might be found. In this regard, the stratigraphic accounts of the dolomite, compiled by Eriksson (1971, 1972), Button (1973a, 1973b) and by Eriksson and Truswell (1974) could act as broad guides. Secondly, an attempt should be made to gain an appreciation of the structural history of the basin, with particular emphasis on faults and fault-systems which cut the Malmani Dolomite. Finally, a knowledge of the diagenetic and cementation history of the carbonates would assist in predicting the history of, and paths taken by, migrating fluids.

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REFERENCES

- Button, A. (1973a). The stratigraphic history of the Malmani Dolomite in the eastern and north-eastern Transvaal. Geol. Soc. S. Afr., Trans., 76, p. 230-247.
- Button, A. (1973b). A regional study of the stratigraphy and development of the Transvaal Basin in the eastern and northeastern Transvaal. Unpub. Ph.D. Thesis, Univ. of the Witwatersrand, 352 pp.
- Button, A. (1974). Iron formation as an end-member in carbonate sedimentary cycles in the Transvaal Supergroup, South Africa. Econ. Geol. Res. Unit, Inform. Circ. No. 89, 10 pp.
- Callahan, W.H. (1966). Paleophysiographic premises for prospecting for stratabound base mineral deposits in carbonate rocks. Nevada Bureau of Mines, Report 13, Part e, p. 5-50.
- Cousins, C.A. (1973). Cyclic sedimentation in the Malmani Dolomite, Potchefstroom Synclinorium. Discussion on paper by K.A. Eriksson, Geol. Soc. S. Afr., Trans., 76, p. 172.

- Deffeyes, K.S., Lucia, F.J., and Weyl, P.K. (1965). Dolomitization of Recent and Plio-Pleistocene sediments by marine evaporite waters on Bonaire, Netherlands Antilles, p. 71-88. In: Pray, L.C. and Murray, R.C. (eds.), Dolomitization and Limestone Diagenesis, Soc. Econ. Pal. Min., Spec. Publ. 13, 180 pp.
- Eriksson, K.A. (1971). A basin analysis of the Transvaal Sequence in the Potchefstroom Synclinorium, Transvaal and Orange Free State. Unpub. M.Sc. Thesis, Univ. of the Witwatersrand, 79 pp.
- Eriksson, K.A. (1972). Cyclic sedimentation in the Malmani Dolomite, Potchefstroom Synclinorium. Geol. Soc. S. Afr., Trans., 75, p. 85-95.
- Eriksson, K.A. and Truswell, J.F. (1974). Stratotypes from the Malmani Subgroup north-west of Johannesburg. Geol. Soc. S. Afr., Trans., 77, p. 211-222.
- Eriksson, K.A., McCarthy, T.S., and Truswell, J.F. (1975). Limestone formation and dolomitization in a Lower Proterozoic succession from South Africa. Jour. Sed. Petrology (in press).
- Goddard, E.N. (1951). Rock-colour chart. Huyskes-Enschede, Netherlands.
- Graf, D.L. (1960). Geochemistry of carbonate sediments and sedimentary carbonates. Illinois State Geol. Surv., Circ. 301, p. 1-71.
- Hem, J.D. (1972). Chemical factors that influence the availability of Fe and Mn in the aqueous system. Geol. Soc. Amer., Bull., 83, p. 443-450.
- Horwood, C.B. (1910). Notes and analyses of typical Transvaal rocks. Trans., Geol. Soc. S. Afr., 13, p. 29-55.
- Jones, K. and Hirst, D.M. (1972). The distribution of barium, lead, and zinc in the Lower and Middle Magnesian Limestone of Country Durham, Great Britain. Chemical Geology, 10, p. 223-236.
- Lepp, H. (1963). The relation of iron and manganese in sedimentary iron formations. Econ. Geol., 58, p. 515-526.
- Roberts, W.M. (1973). Dolomitization and the genesis of the Woodcutters lead-zinc prospect, Northern Territory, Australia. Mineralium Deposita, 8, p. 35-56.
- Truswell, J.F. and Eriksson, K.A. (1975). A palaeoenvironmental interpretation of the Early Proterozoic Malmani Dolomite from Zwartkops, South Africa. Precambrian Research, 2, p. 277-303.
- Turekian, K.K. and Wedepohl, K.H. (1961). Distribution of the elements in some major units in the Earth's crust. Geol. Soc. Amer., Bull., 72, p. 175-192.
- Veizer, J. and Demovic, R. (1973). Environmental and climatic controlled fractionation of elements in the Mesozoic carbonate sequences of the western Carpatheans. Jour. Sed. Petrology, 43, p. 258-271.
- Young, R.B. (1906). The calcareous rocks of Griqualand West. Geol. Soc. S. Afr., Trans., 9, p. 57-66.
- Zietsman, A.L. (1964). The geology of the Sabie-Pilgrims Rest Goldfield. Unpub. M.Sc. Thesis, Univ. of the Orange Free State, 84 pp.

APPENDIX

CHEMISTRY OF THE MALMANI DOLOMITE

HCl denotes reaction with dilute hydrochloric acid (0 = very weak,
3 = strong).

Col denotes colour (lightness) index of dolomite (1 = black,
9 = white).

Re-x denotes recrystallization (1 = fine-grained crystalline,
3 = strongly recrystallized).

Cht denotes visible chert (1 = absent, 3 = present in small amounts).

Sample	Fe ₂ O ₃ (%)	MgO (%)	CaO (%)	MnO (%)	Zn ppm	Pb ppm	HCl	Col	Re-x	Cht	CaO/ MgO	SiO ₂ (%)
001	3,30	17,9	25,7	0,55	44	18	0,0	4,0	2,0	1,0	1,44	6,19
002	2,87	18,7	25,7	0,43	27	18	0,0	4,5	1,0	1,0	1,37	6,19
003	2,09	20,5	28,2	0,40	37	18	0,0	4,5	2,0	1,0	1,38	2,45
004	1,49	11,0	17,4	0,20	39	18	0,0	4,5	2,0	3,0	1,58	31,30
005	1,34	18,5	25,2	0,22	36	22	0,0	4,5	1,0	1,0	1,36	9,29
006	0,83	16,5	24,2	0,21	23	22	0,0	4,5	1,0	1,0	1,47	13,69
007	1,23	18,5	25,3	0,19	26	22	0,0	4,5	1,0	1,0	1,37	7,66
008	1,30	13,6	20,3	0,11	44	17	0,0	4,5	1,0	1,0	1,49	23,31
009	0,93	13,1	19,5	0,11	31	17	0,0	4,5	1,0	2,0	1,49	25,59
010	0,68	22,3	24,2	0,14	20	21	0,0	4,5	2,0	1,0	1,09	4,40
011	0,74	22,4	28,2	0,25	55	23	0,0	4,5	2,0	1,0	1,26	3,10
012	0,64	22,9	29,3	0,20	28	25	0,0	4,5	2,0	1,0	1,28	1,14
013	0,47	19,0	25,7	0,20	60	20	0,0	5,0	3,0	1,0	1,35	9,78
014	0,51	23,8	28,2	0,18	32	22	0,0	4,5	2,0	1,0	1,18	2,12
015	0,78	19,7	24,7	0,14	85	23	0,0	4,5	2,0	1,0	1,25	9,29
016	0,52	23,0	29,6	0,18	81	21	0,0	5,5	1,5	1,0	1,29	0,65
017	0,67	23,4	28,8	0,15	51	23	0,0	5,0	1,5	1,0	1,23	1,63
018	0,64	18,2	24,1	0,15	42	21	0,0	4,5	1,0	1,0	1,32	14,18
019	0,68	22,3	30,0	0,38	78	15	0,0	4,5	2,0	1,0	1,35	1,14
020	0,58	22,5	29,5	0,38	50	15	0,0	4,5	2,0	1,0	1,31	0,82
021	0,74	22,4	29,8	0,35	67	20	0,0	5,5	1,5	1,0	1,33	26,57
022	0,96	21,4	29,3	0,29	15	23	0,0	5,0	1,5	1,0	1,37	2,45
023	0,67	21,7	29,6	0,25	11	23	0,0	4,5	1,0	1,0	1,36	1,30
024	0,68	22,1	29,7	0,22	12	22	0,0	4,5	1,5	1,0	1,34	0,65
025	0,58	14,6	21,8	0,16	17	15	0,0	5,5	1,0	1,0	1,49	21,35
026	0,80	22,3	30,0	0,34	80	26	0,0	4,5	1,0	1,0	1,35	0,65
027	1,00	21,1	28,0	0,18	48	23	0,5	5,0	3,0	1,0	1,33	4,08

028	0,85	21,9	29,8	0,18	97	27	0,0	5,0	3,0	1,0	1,36	1,30
029	0,71	18,4	24,9	0,18	138	22	0,0	5,0	2,0	1,0	1,35	10,27
030	0,57	22,1	29,6	0,27	89	22	0,5	5,0	2,0	1,0	1,34	0,82
031	0,89	22,0	29,1	0,24	63	19	0,0	5,0	2,0	2,0	1,32	1,30
032	1,06	21,9	29,1	0,17	50	20	0,0	5,5	1,5	1,0	1,33	1,79
033	1,35	20,6	28,1	0,18	131	22	0,0	5,5	2,0	3,0	1,36	4,89
034	0,70	22,5	29,0	0,16	94	25	0,0	5,0	2,0	1,0	1,29	1,63
035	0,40	23,6	29,2	0,19	69	24	0,0	5,0	1,5	1,0	1,24	0,49
036	0,40	23,4	29,6	0,29	54	18	0,0	5,0	1,5	1,0	1,26	0,65
037	0,24	23,7	29,4	0,25	92	22	0,0	6,0	1,5	1,0	1,24	0,33
038	0,33	23,8	29,7	0,21	110	25	0,0	6,0	1,5	2,0	1,25	0,49
039	0,42	23,6	29,4	0,36	52	25	0,0	6,0	1,5	1,0	1,25	0,65
040	0,59	22,6	29,6	0,44	121	20	0,0	5,5	1,5	1,0	1,31	0,98
041	0,69	23,3	29,6	0,44	53	23	0,0	5,5	1,5	1,0	1,27	0,49
042	1,18	22,2	28,5	0,23	73	15	0,0	4,5	1,5	1,0	1,28	2,45
043	0,69	14,1	21,1	0,09	54	11	0,0	5,0	2,0	2,0	1,50	23,47
044	0,70	18,8	25,4	0,09	36	18	0,0	5,0	2,0	1,0	1,35	11,4
045	0,74	23,0	29,9	0,10	63	25	0,0	6,0	1,5	1,0	1,30	0,65
046	0,75	22,5	29,2	0,12	95	25	0,0	6,0	1,5	2,0	1,30	1,63
047	0,36	23,1	29,6	0,08	52	25	0,0	6,0	1,5	2,0	1,28	0,98
048	0,42	22,4	27,9	0,12	81	20	0,0	6,0	1,5	1,0	1,25	3,26
049	0,26	23,7	29,4	0,12	106	21	0,0	6,0	1,5	1,0	1,24	0,16
050	0,21	23,7	29,8	0,13	72	24	0,0	6,0	1,5	1,0	1,26	0,16
051	0,40	23,1	29,1	0,13	53	19	0,0	6,0	1,5	1,0	1,26	0,33
052	0,73	21,1	28,4	0,36	111	19	0,0	4,5	2,0	1,0	1,35	2,77
053	0,33	21,9	28,8	0,28	95	23	0,0	5,5	3,0	1,0	1,32	1,79
054	0,27	22,2	29,8	0,33	62	22	0,0	6,0	3,0	1,0	1,34	0,98
055	0,27	23,4	29,0	0,32	93	22	0,0	6,0	2,0	1,0	1,24	0,98
056	0,33	22,1	29,1	0,31	150	22	0,0	6,0	2,0	1,0	1,32	1,48
057	0,44	22,3	29,6	0,20	220	16	0,0	6,0	1,5	1,0	1,34	0,49
058	0,43	22,4	29,9	0,26	96	20	0,0	6,0	1,5	1,0	1,33	0,49
059	0,53	21,8	29,2	0,22	121	20	0,0	5,5	1,5	2,0	1,34	2,12
060	1,43	17,6	25,5	0,24	300	13	0,0	4,0	2,0	2,0	1,45	10,76
061	2,41	13,6	20,7	0,25	134	13	0,0	3,5	1,0	1,0	1,52	16,63
063	0,57	21,0	30,2	0,91	107	17	1,0	4,0	1,5	1,0	1,44	1,30
064	0,38	20,5	30,4	1,04	124	22	1,0	4,5	1,5	1,0	1,48	0,98
065	0,41	20,7	30,6	1,08	113	18	0,0	4,5	1,5	1,0	1,48	0,65

066	0,48	20,9	30,7	0,90	119	22	0,0	4,5	2,0	1,0	1,47	0,33
067	0,66	20,8	30,1	1,01	150	22	1,0	4,0	1,5	1,0	1,45	2,98
068	1,71	19,9	29,6	1,55	121	21	0,0	5,5	1,5	1,0	1,49	1,47
069	0,56	20,7	30,4	1,92	166	17	0,0	4,0	1,5	1,0	1,47	0,49
070	0,55	20,5	29,5	1,79	104	14	0,0	4,5	2,0	1,0	1,44	0,82
071	0,47	20,1	30,0	1,42	117	20	0,0	4,0	1,5	1,0	1,49	1,30
072	0,35	20,6	30,3	1,11	75	15	0,0	4,0	1,5	1,0	1,47	0,33
073	0,33	20,8	30,4	0,82	79	19	0,5	4,5	2,0	1,0	1,46	0,33
074	0,41	20,5	30,1	0,61	67	15	0,0	4,0	2,0	1,0	1,47	0,49
075	0,86	19,2	27,9	0,51	65	23	0,0	4,5	2,5	1,0	1,45	5,22
076	1,90	18,3	28,1	0,55	94	18	0,0	4,0	1,5	2,0	1,54	4,56
077	0,84	20,6	30,4	0,87	89	22	0,0	4,5	1,5	1,0	1,48	0,65
078	0,30	21,4	30,5	0,47	80	28	0,0	4,5	2,5	1,0	1,43	0,65
079	0,48	20,9	30,0	0,44	63	25	0,0	4,5	1,5	1,0	1,44	1,14
080	0,39	20,2	29,3	0,45	56	22	0,0	4,5	1,5	1,0	1,45	2,93
081	0,73	20,6	29,2	0,46	49	15	0,0	4,0	1,5	1,0	1,42	1,63
082	1,83	15,0	24,4	0,31	25	15	0,0	4,0	2,0	2,0	1,63	13,69
083	0,57	20,1	29,1	0,40	48	23	0,0	4,5	3,0	2,0	1,45	3,75
084	0,62	16,8	26,2	0,39	58	18	1,0	4,0	1,5	1,0	1,56	8,97
085	0,40	20,0	29,1	0,55	77	22	0,5	4,0	2,0	1,0	1,46	2,77
086	0,29	20,7	29,2	0,51	91	25	0,0	4,5	2,0	1,0	1,41	2,77
087	0,30	20,6	29,0	0,56	81	20	0,0	4,5	1,5	1,0	1,41	2,28
088	0,31	18,8	27,8	0,57	33	25	0,0	4,5	2,0	2,0	1,48	5,88
089	0,47	21,6	30,1	0,50	28	19	0,0	5,0	3,5	1,0	1,39	0,49
090	0,41	17,9	27,4	0,36	28	12	0,0	4,5	2,0	1,0	1,53	6,52
091	0,32	19,8	28,1	0,45	21	18	0,0	4,5	2,0	1,0	1,42	4,56
092	0,47	17,7	28,0	0,42	32	16	0,0	4,5	2,5	2,0	1,58	6,36
093	1,01	16,9	25,8	0,37	38	17	1,0	5,5	3,0	1,0	1,53	10,92
094	0,44	20,8	30,0	0,52	235	24	0,0	5,0	1,5	1,0	1,44	0,98
095	0,33	21,3	30,4	0,48	265	21	0,0	5,0	2,0	1,0	1,43	0,49
096	0,39	21,2	30,3	0,48	185	22	0,0	5,0	3,0	1,0	1,43	0,65
097	0,56	20,8	29,5	0,36	160	24	0,0	4,5	2,5	1,0	1,42	1,79
098	0,58	19,5	30,4	0,37	160	19	0,0	4,5	2,0	1,0	1,56	0,65
099	0,30	20,1	30,7	0,35	185	24	0,0	4,0	1,5	1,0	1,53	0,49
100	0,61	19,1	30,7	0,43	156	24	0,5	4,0	2,0	1,0	1,61	0,98
101	0,56	18,7	31,5	0,44	185	17	0,0	4,5	2,5	1,0	1,68	0,49
102	0,45	18,9	31,6	0,48	147	24	0,0	5,0	2,5	1,0	1,67	0,16
103	0,52	19,4	30,7	0,48	146	23	0,0	5,0	2,5	1,0	1,58	0,49

104	1,07	14,1	24,0	0,42	180	20	0,0	4,5	3,0	2,0	1,70	15,00
105	0,94	18,2	29,8	0,51	285	14	0,0	5,0	2,0	1,0	1,64	2,45
106	0,60	19,7	29,8	0,44	195	17	0,0	4,5	2,0	1,0	1,51	1,79
107	0,56	20,3	30,2	0,46	185	19	0,0	4,5	1,5	1,0	1,49	0,65
108	0,45	17,7	28,7	0,33	210	22	0,5	4,5	1,5	1,0	1,62	4,40
109	0,43	20,0	31,0	0,41	215	23	0,5	4,5	2,0	1,0	1,55	0,16
110	0,39	19,9	31,1	0,41	170	24	0,0	4,5	1,5	1,0	1,56	0,33
111	0,69	19,8	31,3	0,48	131	2,5	0,0	4,0	1,5	1,0	1,58	0,33
112	0,69	20,0	31,1	0,47	132	13	0,0	4,0	1,5	1,0	1,58	0,49
113	0,66	18,7	30,9	0,44	185	30	0,0	4,0	1,5	1,0	1,56	1,47
114	1,10	18,5	30,8	0,59	120	23	0,0	4,5	3,0	1,0	1,65	0,98
115	1,13	19,8	30,7	0,59	250	26	0,0	4,5	2,5	1,0	1,55	0,98
116	5,73	13,8	31,1	2,23	180	10	0,0	4,0	1,5	1,0	2,25	1,63
117	5,08	16,0	30,3	1,30	147	12	0,0	3,5	1,5	1,0	1,89	1,47
118	1,96	3,49	47,5	1,08	138	6	3,0	3,5	1,5	1,0	13,61	1,47
119	0,82	1,31	49,6	0,85	165	5	3,0	4,0	2,0	1,0	37,86	2,77
120	0,73	0,91	50,3	0,82	130	2,5	3,0	3,5	2,0	1,0	55,27	2,46
121	1,93	18,5	29,4	1,22	165	20	0,0	4,0	1,0	1,0	1,59	2,77
122	1,31	18,5	30,1	1,04	160	22	0,0	4,0	1,5	1,0	1,63	2,12
123	1,15	18,6	29,7	0,81	122	22	0,0	4,0	1,5	1,0	1,60	2,28
124	1,29	14,5	23,4	0,72	150	17	0,0	4,5	1,5	1,0	1,61	16,14
125	1,24	20,2	29,3	0,87	130	22	0,0	5,0	1,5	1,0	1,45	1,79
126	1,84	15,9	29,5	1,03	117	19	1,0	5,0	1,5	1,0	1,86	4,24
127	2,60	12,9	25,3	1,13	139	13	1,0	5,0	1,5	1,0	1,96	11,57
128	0,64	1,76	48,3	0,70	96	5	3,0	3,5	1,5	1,0	27,44	3,91
129	0,76	1,54	47,9	0,74	133	7	3,0	4,0	1,5	1,0	31,10	4,89
130	0,87	1,13	49,3	0,77	113	7	3,0	3,5	1,5	1,0	43,63	4,24
131	0,88	1,57	48,5	0,67	117	8	3,0	4,0	2,0	1,0	30,89	4,89
132	2,61	16,6	29,7	0,94	137	12	2,0	4,0	2,0	1,0	1,79	3,91
133	2,26	20,2	29,8	0,46	71	14	0,5	4,0	1,5	1,0	1,48	1,14
134	2,70	20,3	30,3	0,64	310	20	0,0	4,5	2,5	1,0	1,49	0,16
135	3,76	18,7	29,5	0,59	270	15	0,0	4,0	1,5	1,0	1,58	1,30
136	2,17	20,4	30,3	0,49	225	17	0,0	5,0	3,0	1,0	1,49	0,16
137	2,30	20,7	30,4	0,51	245	19	0,0	5,0	3,0	1,0	1,47	0,16
138	3,87	18,9	30,8	0,71	280	16	0,0	4,5	1,5	1,0	1,63	0,16
139	2,80	20,5	30,4	0,54	205	16	0,0	4,5	2,5	1,0	1,48	0,16
140	2,62	20,4	30,5	0,49	225	18	0,0	4,5	2,0	1,0	1,50	2,28
141	4,65	19,3	30,6	0,51	335	17	0,0	4,5	1,5	1,0	1,59	0,33

142	3,78	19,6	30,4	0,54	185	20	0,0	4,5	1,5	1,0	1,55	0,33
143	3,86	18,7	29,7	0,43	205	21	0,5	4,0	1,5	1,0	1,59	2,45
144	3,37	19,7	30,9	0,50	195	15	0,0	4,0	1,5	1,0	1,57	0,49
145	5,83	6,28	19,5	0,40	200	12	2,0	4,0	1,0	1,0	3,11	27,06
146	1,28	1,56	35,5	0,32	220	15	3,0	4,5	2,0	1,0	22,76	7,01
147	4,23	5,20	23,0	0,51	235	16	2,0	4,0	1,0	1,0	4,42	11,41
148	2,13	1,62	42,2	0,38	190	9	3,0	5,0	2,0	1,0	26,05	10,92
149	0,57	0,67	29,4	0,22	205	12	2,5	4,5	1,5	1,0	43,88	34,72
150	1,61	2,17	42,5	0,44	230	7	3,0	4,5	2,5	1,0	19,59	8,97
151	2,19	1,48	41,7	0,62	158	8	3,0	4,0	1,0	1,0	28,18	11,25
152	1,18	1,02	50,6	0,48	150	11	3,0	4,0	1,5	1,0	49,61	3,91
153	7,70	2,56	31,4	0,39	153	2,5	2,5	3,5	1,0	1,0	12,27	16,30

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