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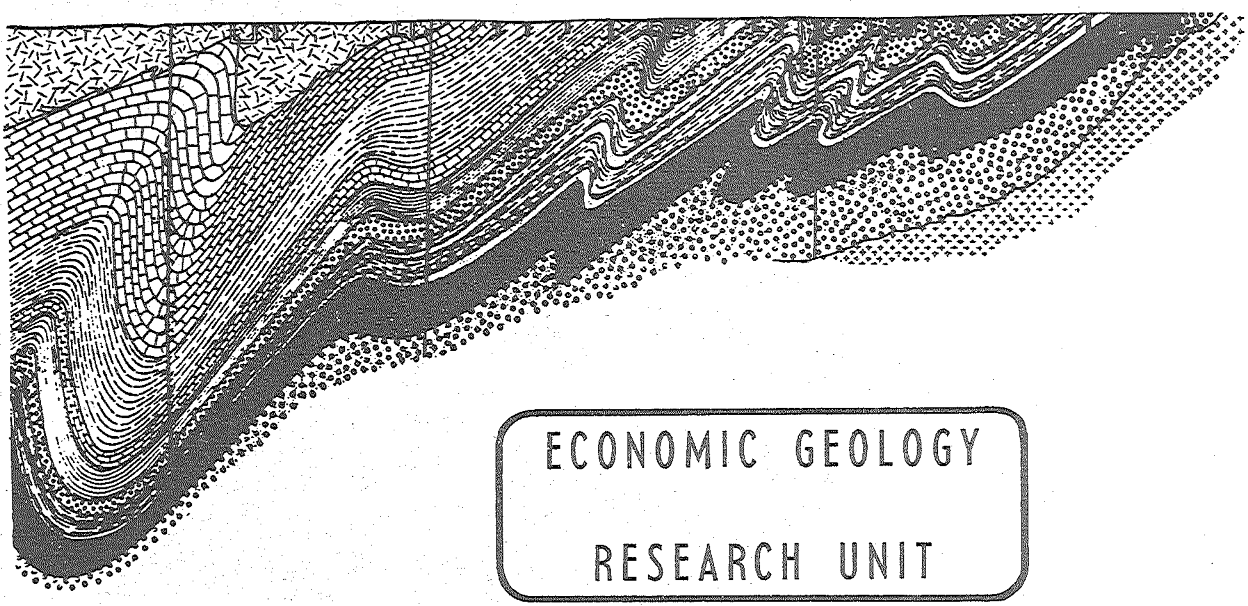

ECONOMIC GEOLOGY

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INFORMATION CIRCULAR No. 30

A COMPARISON OF PEBBLE AND FOLD DEFORMATIONS IN THE NELSPRUIT GRANITE CONTACT AUREOLE

C. R. ANHAEUSSER

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by

C. R. ANHAEUSSER

Research Fellow

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ABSTRACT

The percentage flattening of pebbles of deformed conglomerates from the Moodies Series of the Eureka Syncline was calculated and compared with values obtained for the combined shortening and flattening of tight isoclinal folds found in Fig Tree strata of the Lily Mine, a gold mine situated six miles east of the pebble occurrences.

For both the fold and pebble deformation examples, only the amount of flattening suffered by the rocks could be calculated directly. Empirical values reflecting the shortening of the formations during the initial stages of deformation were added to the calculated values in order to obtain a measure of the total deformation that affected the area.

The mine folds were found to be shortened and flattened by approximately 63 per cent while the mean pebble deformation amounted to approximately 61 per cent; a striking parallelism.

Both the conglomerate and fold localities occur in the outer greenschist zone of a contact metamorphic aureole produced by the emplacement of the intrusive phase of the Nelspruit Granite along the contact with the Archaean successions in the northern part of the Barberton Mountain Land. The example, suggests also that in this particular case the cleavage or "similar" folding was the direct consequence of flattening processes with shearing only of secondary importance in the production of the fold deformation.

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CONTENTS

	Page
INTRODUCTION	1
THE BASAL CONGLOMERATE OF THE EUREKA SYNCLINE	1
A. LITHOLOGY	1
B. CLASSIFICATION	2
C. STRUCTURE OF THE CONGLOMERATES	2
D. PEBBLE SAMPLING	2
E. PERCENTAGE DEFORMATION OF THE CONGLOMERATE PEBBLES	3
F. GENERAL DISCUSSION	5
FOLD DEFORMATION IN THE LILY GOLD MINE	6
A. GEOLOGICAL ENVIRONMENT OF THE MINE	6
B. STRUCTURE	7
C. FOLD DEFORMATION ANALYSES	7
COMPARISON OF PEBBLE AND FOLD DEFORMATION DATA	8
GENERAL DISCUSSION	9
Acknowledgements	10
List of References Cited	10
Key to Figures	11

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A COMPARISON OF PEBBLE AND FOLD DEFORMATIONS IN THE NELSPRUIT GRANITE CONTACT AUREOLE

INTRODUCTION

In a recent detailed structural investigation of the area northeast of Barberton a comparison was made between the extent of deformation suffered by conglomerate pebbles in the Moodies Series and isoclinal folds in strata of the Fig Tree Series of the Swaziland System.

Two localities exist where basal conglomerates of the Moodies Series are conspicuously flattened and deformed. The first of these is in the Lily Syncline between Joe's Luck Siding and Louw's Creek where a considerable thickness of the formation is composed of conglomerates and quartzites. The second locality occurs to the south of the Lily Syncline and forms the basal conglomerate of the Eureka Syncline.

The latter occurrence is well exposed in several cuttings along the Noordkaap-Kaapmuiden road, especially between Joe's Luck Siding and Eureka Siding.

Excellent underground exposures of tight isoclinal folds were found in the Fig Tree successions of the Lily Gold Mine approximately three miles south of Louw's Creek Station. The extent of the fold deformation from the mine area was compared with the pebble deformation of the conglomerate horizon which occurs approximately six miles due west of the mine.

In both these localities the formations strike approximately east-west and the bedding is regionally steeply dipping to the south. In addition, both localities have suffered almost identical low grade metamorphism and occur on the outer margin of the contact aureole produced by the intrusive phase of the Nelspruit Granite (Anhaeusser and Viljoen, 1965).

THE BASAL CONGLOMERATE OF THE EUREKA SYNCLINE

A. LITHOLOGY

The basal conglomerate of the Moodies Series is composed mainly of pebbles and boulders of black chert, banded ironstone, red banded jasper, grit, quartzite, quartz porphyry and granitic rock. The pebbles occur in an arenaceous matrix of gritty shale, graywacke or impure quartzitic material. The conglomerates are locally extensively deformed as for example in the areas discussed in this paper. A strong cleavage was superimposed on the conglomerates during deformation.

Chert pebbles are by far the most abundant pebble types encountered in the conglomerate horizons and were probably derived from the erosion of the Onverwacht and Fig Tree Series rocks underlying the Moodies succession.

Quartzitic and granitic pebbles were found less frequently while jaspers and pebbles of acid lava and shale appear only locally.

Pebble-free bands occur in places throughout the conglomerate but appear to be more common near the top of the succession. The pebble layers grade laterally into grits and sandstones with even some calcareous material present at times.

B. CLASSIFICATION

The Moodies conglomerate in general, conforms to Pettijohns definition (Pettijohn, 1957) of a polymictic conglomerate. In undeformed areas the conglomerate is often of considerable size and contains a wide variety of well defined pebbles in a matrix of sandstone and graywacke.

C. STRUCTURE OF THE CONGLOMERATES

The pebbles in the conglomerates in both the Lily Syncline and the Eureka Syncline are generally flattened elongated ellipsoids (Plate 1, Figures 1 and 2). The longest pebble axes are approximately parallel and the conglomerate in places, displays a marked lineation.

In the Joe's Luck Siding area the lineation of the deformed and elongated pebbles, plunges at intermediate angles to the northwest while the planes of bedding and cleavage dip steeply to the northeast on an ESE-trending strike (Viljoen, 1964).

Further to the east the writer (Anhaeusser, 1964) showed that in the Sheba and Eureka Siding areas outcrops of the elongated pebbles displayed a lineation that plunged almost vertically in very steeply dipping, east-west-striking beds.

In addition the regional structural investigations in the area showed that the pebble lineations in the conglomerate and the lineations found in a quartz-sericite schist horizon to the north of Eureka Siding were probably related to the same deformational event that was responsible for the strong folding of the Fig Tree formations of the Lily Gold Mine.

In this area too, the axial plane cleavage, schistosity and bedding of all the rocks have the same orientation indicating that the folding must be of an isoclinal nature.

D. PEBBLE SAMPLING

Viljoen (1964) was able to extract and measure the deformed pebbles from their partly decomposed and weathered matrix in the areas both north and southwest of Joe's Luck Siding. He found that the amount of deformation for both areas was identical. Further to the east the writer (Anhaeusser, 1964) found that the conglomerate pebbles in the Lily Syncline were tightly cemented together and it was impossible to obtain three dimensional specimens for study. Pebbles could, however, be extracted from the basal conglomerate of the Eureka Syncline where good exposures occur in road cuttings near Sheba Siding and Eureka Siding.

In this paper, the three major axes of the pebbles are termed A, B, and C where $A > B > C$ (after Cloos, 1947). The A, B, and C dimensions of 63 deformed pebbles varying in size from an inch to over one foot were studied separately by Viljoen (1964) who measured 35 pebbles in the Joe's Luck Siding area and by the writer (Anhaeusser, 1964) who measured 28 pebbles in the Sheba-Eureka Siding area.

These results were compared with 35 pebbles of undeformed Moodies conglomerate, collected about ten miles south-southeast of the above localities in the heart of the Mountain Land, where they are exposed on the Shia-Lo-Ngubu-Barberton road. Flinn (1956) stated that for statistical treatment, at least 30 pebbles should be measured at each station. Broadly, therefore, the data collected for the purpose of this study conforms to these requirements.

Tabulated data on the A:B:C ratios for both the deformed and undeformed pebble types is listed in Table 1.

TABLE 1

RATIOS OF DEFORMED AND UNDEFORMED
CHERT AND GRANITIC OR QUARTZITIC PEBBLES

Pebble Type	State of Pebble	A:B:C	Locality
Chert	Undeformed	5:4:3	Shia-Lo-Ngubu Area
Chert	Deformed	5:3:1.25	Joe's Luck Siding Area
Chert	Deformed	5:3:1.20	Sheba-Eureka Siding Area
Granitic and Quartzitic	Undeformed	5:4:3.50	Shia-Lo-Ngubu Area
Granitic and Quartzitic	Deformed	5:3.40:2.60	Joe's Luck Siding Area

E. PERCENTAGE DEFORMATION OF THE CONGLOMERATE PEBBLES

Using the results tabulated in Table 1 the percentages of deformation in the A, B, and C dimensions for the chert pebbles were calculated. The assumption was made that the original pebbles were either spherical or randomly orientated triaxial ellipsoids and the following formula for a unit sphere was used :

$$d = \sqrt[3]{a.b.c.}$$

where d is the radius of a sphere having the same volume as a triaxial ellipsoid in which the half-axial lengths are a, b and c.

NOTE: In the above formula the half-axes (a, b, and c) are employed. As ratios are involved, the use of the full axial lengths A, B, and C does not influence the result.

The value D was calculated and after substituting the values of A, B, and C in the formula

$$A = \frac{A-D}{D} \times 100 \text{ for } A, \text{ etc.}$$

the following results were obtained for the separate occurrences at Joe's Luck Siding and at Sheba-Eureka Siding.

(a) for chert pebbles:

	Joe's Luck Siding	Sheba-Eureka Siding
A percentage elongation in A of	87.60%	90.07%
A percentage elongation in B of	12.46%	14.50%
A percentage decrease in C of	53.20%	54.20%

(b) for granitic and quartzitic pebbles :

	Joe's Luck Area
A percentage elongation in A of	41.00%
A percentage decrease in B of	3.70%
A percentage decrease in C of	27.00%

From the ratios obtained from undeformed pebbles (Table 1) it is, however, clear that the pebbles in their original form, prior to deformation, were not spherical but invariably ellipsoidal in shape. In addition Ramsay (1963) showed that the long axis orientations of the pebbles were not completely random but were arranged at all azimuths in a plane that defined the bedding.

On the new assumptions, therefore, that the pebbles were invariably triaxial ellipsoids the values for A, B, and C were again calculated, this time using the formula for a unit ellipsoid:

$$\text{Volume of ellipsoid} = \frac{4\pi\ a,\ b,\ c}{3}$$

Again, by substituting the values A, B, and C in the formula, the problem is not affected as ratios are involved.

The percentage deformation in A, B, and C directions was calculated using the relationship

$$\frac{A1 - A}{A} \times 100 = \text{percentage deformation in A.}$$

where A = value for undeformed pebbles

and A1 = value for deformed pebbles

In the same way values for B and C were calculated. The following results were obtained:

(a) for chert pebbles

	Joe's Luck Siding	Sheba-Eureka Siding
A percentage elongation in A of	47.40%	49.20%
A percentage elongation in B of	10.55%	12.25%
A percentage decrease in C of	38.60%	40.03%

(b) for granitic and quartzitic pebbles

	Joe's Luck Siding
A percentage elongation in A of	16.00%
A percentage decrease in B of	2.87%
A percentage decrease in C of	14.00%

From the results it is clear that the percentage deformation in the A and C directions is considerably greater for chert pebbles than it is for granitic and quartzitic types and, in addition, there is never, in the case of both rock categories, a large deformation in B; the mean axis of the pebble.

In the relationship $\frac{A1 - A}{A} \times 100$ = percentage deformation in A, the assumption is made that the original long dimension (A) of the undeformed pebble, parallels the deformed long dimension (A1). This will only rarely occur with the result that normally the relationship will be

$$\frac{A1 - X}{X} \times 100,$$ where X is any value less than A, lying between A and C.

As X becomes smaller and tends towards C, the ratio of the above relationships becomes larger and thus the value for the percentage deformation increases. The values shown earlier, therefore, represent an absolute minimum value of the percentage deformation and are probably more or less indicative of the amount of deformation suffered by the whole conglomerate zone in the area between Joe's Luck Siding and Eureka Siding.

In addition to the pebble flattening many chert pebbles exhibited a slight twisting or buckling of the flattened "ab" planes of the pebbles themselves. This effect was caused either by some rotation during deformation or else by the "moulding" effect imprinted by adjacent pebbles on to one another during flattening (Viljoen, 1964).

The part played by shearing in the deformation of the pebbles was not considered in this discussion as Ramsay (1963) believed it to be almost impossible to distinguish it's effects from those of pure flattening.

F. GENERAL DISCUSSION

Several assumptions have been made with regard to the pebble data analyses. In the first instance, there is no absolute method of determining the original orientation of the conglomerate pebbles prior to their deformation. It has, therefore, been assumed that the two long axes of the pebbles lay in the plane of the bedding.

Several reasons can be given in support of this assumption. Firstly, the Geological Survey (Visser, et. al. 1956) showed that the pebbles of the Moodies basal conglomerate were almost without exception, orientated with their major axes in the direction of dip of the strata containing them. "Crustal shortening", they stated, "was aminly at right angles to the strike of the Mountain Land and was taken up by the elongation of beds radially in a vertical direction". Pebbles in the conglomerates of the Moodies Series were found by the Geological Survey to be orientated with their major axes at right angles to the direction of strike of the folds which are either vertical or steeply inclined to the south.

Furthermore, Ramsay (1963) showed that in an area approximately 5.5 miles east-southeast of Barberton the long axes of undeformed conglomerate pebbles were orientated in all directions within a plane which represented the bedding.

Structural investigations in the Barberton Mountain Land by Ramsay (1963) also showed that there was a strong development of cleavage that was superimposed upon first fold structures in the area.

He further noted that the deformed pebbles south of the Kaap River, and west of Joe's Luck Siding had a prefered linear orientation within the plane of slaty cleavage resultant from intense tectonic elongation overprinted on the initial sedimentary fabric. In this area the superimposed cleavage was developed obliquely to the bedding of the strata. In other words, therefore, the pebbles had been elongated here, in the plane of the cleavage.

It was fortunate from the point of view of this study, however, that in the area further to the east between Joe's Luck Siding and Eureka Siding the bedding and the superimposed cleavages were found to be coincident. Thus the pebbles lay flattened in the cleavage plane which in this case was parallel to the bedding plane.

Had the cleavage cross-cut the conglomerates an absolute value of the percentage shortening would not have been obtained. For example, if the pebbles were flattened in the plane of the cleavage and bedding which were coincident, then the shortest axis (C) of the pebbles would have been shortened still further by flattening to (C1),

$$\text{where } \frac{C - C1}{C} \times 100 \text{ percentage shortening in C.}$$

Had the pebbles been flattened in planes of cleavage which were not coincident with the bedding planes then the shortest axis (C1) of the deformed pebble would have resulted from the compression and flattening of X, a value greater than (C), viz: the shortest axis of the original ellipsoidal pebble.

Thus, because the assumption has been made that the original short dimension (C) of the undeformed pebble parallels the short dimension (C1) of the deformed pebble it can be concluded that the values obtained for C represent the true value of shortening while the values obtained for the other may be unrealistic because there is no control of the orientation of A and B prior to deformation.

FOLD DEFORMATION IN THE LILY GOLD MINE

A. GEOLOGICAL ENVIRONMENT OF THE MINE

The Lily Mine occurs approximately 30 miles northeast of Barberton and about three miles south of Louw's Creek Station. In relationship to the conglomerate horizon from which the foregoing percentages of pebble deformation were calculated, the mine is situated about six miles due east in Fig Tree Series rocks underlying the Moodies successions of the Eureka Syncline.

As mentioned earlier both the pebble occurrences and the formations in which the mine is situated fall into the outer, low temperature, greenschist facies of the contact metamorphic aureole produced by the intrusive border phase of the Nelspruit Granite (Anhaeusser and Viljoen, 1965).

Very locally in the mine, however, higher grades of metamorphism were encountered that were associated with hydrothermal solutions responsible for the gold and sulphide mineralization.

The mine is situated in rocks grouped with the lower portion of the Fig Tree Series. The banded ironstones, shales and graywackes abut against talcose schists of the Onverwacht Series. The two Series are separated by the Lily Fault described by the writer (Anhaeusser, 1965) as a longitudinal high-angle thrust fault that was reactivated at a later stage forming a wrench fault.

The fault is marked by a sheared, brecciated zone approximately 30 feet wide in places.

South of the fault zone (Main Reef Horizon in the Lily Mine), the formations become more regular and consist of alternating light and dark ferruginous shales and gray-wackes that have been extensively folded and sheared.

B. STRUCTURE

The formations in the mine strike approximately east-west and the beds dip almost vertically. Apart from the main fault described earlier these are numerous shears parallel to the formations that are also mineralized.

The folding throughout, is of a "similar" type. Tight isoclinal folds were noted on all levels of the underground workings. These folds are characterized by narrow wave lengths and exceptionally long amplitudes.

A pye diagram plot of fold axial planes (Anhaeusser, 1964), indicated a concentration of poles dipping at high angles both to the north and south in addition to vertical fold axes.

The folds in the mine plunge steeply to the east and show a spread of poles indicating either, differential compression of the folds and hence a variation in the "a" tectonic movement direction or, alternatively, superimposed folding. Cleavage associated with the folding was not always clearly visible as it lay parallel to the bedding planes which were in turn, parallel to the axial planes of the folds.

C. FOLD DEFORMATION ANALYSES

Ramsay (1962) developed a method by which an estimate of the amount of flattening in folds could be calculated. The method was based entirely on the thickness of a competent bed or unit measured at any point in the fold and the observed angle of inclination between the bedding and the axial plane of the fold.

Several folds in the mine workings were photographed (Plate 2, Figures 3 and 4) and later enlarged several times for use in an attempt to determine the approximate amount of flattening suffered by the Fig Tree successions in the mine.

The values obtained by this method were then plotted on a graph (Plate 2, Figure 5, after Ramsay, 1962) and the resultant curves gave flattening values of 37 per cent and 46 per cent respectively. An average value of 42 per cent, therefore, represented the approximate amount of flattening additional to the earlier 36 per cent shortening of the formations as they underwent flexure folding. De Sitter (1958) calculated that crustal shortening by the method of flexure folding alone could never exceed 36 per cent of the original length of the beds. He suggested that one method by which crustal shortening could be further developed was by flattening the previously formed flexure fold.

"Flattening" was defined by de Sitter (1958) as the process of deformation whereby an original rock shape is plastically changed by compression. This compression results in contraction in a direction parallel to that of the principle compressive stress and in expansion at right angles to this in the direction of minimum stress.

Thus the entire succession of Fig Tree rocks in the Lily Mine area has undergone an approximate total shortening of about 63 per cent. This figure was derived as follows :

$$36\% + (42\% \text{ of } 64\%) = 63\%$$

COMPARISON OF PEBBLE AND FOLD DEFORMATION DATA

A comparison of the deformation of the pebbles and the folds from the two separate areas discussed in this paper indicated that the average value of flattening of the pebbles, viz., a 39 per cent decrease in the C axis, practically coincided with the average flattening value of 42 per cent derived from the folds in the Lily Mine.

Although these values compare remarkably well they do not, however, reflect the total amount of shortening undergone by the formations. This was shown earlier to be approximately 63 per cent in the case of the mine folds.

The writer considers that the degree of flattening deformation suffered by the two entirely heterogeneous structural parameters coincides so favourably that it allows several possible conclusions to be drawn.

Firstly, the flattening reflected by the conglomerate pebbles would appear to have been initiated only after flexure folding of the formations had been completed. This implies, therefore, that the pebbles in the conglomerate had been relatively little disturbed by the initial flexure folding and that it was only after the flexure folding had been modified by flattening that any pebble deformation took place.

To understand this more fully the problem reverts to the structural evolution of the Eureka Syncline which is generally regarded as a folded succession of Moodies rocks that has suffered a later, superimposed deformation, resulting in the formation of a great arcuate structure. The structural history of the Syncline was investigated by Ramsay (1963) and again later by the writer. It is possible to show that at least four stages of deformation affected the area. The initial folding of the Moodies strata took place at the time of the Main Phase of deformation (F1), which affected the entire Barberton Mountain Land. The (F1) deformational event is considered to have produced a massive "similar type" fold structure (the Eureka Syncline) which initially trended approximately in an ENE direction. (The entire Syncline underwent inflection into a massive arcuate fold later in the structural history, i.e. during the F3 or Consort Trend period of deformation).

Reverting to the evolution of the Main Phase (F1) deformation, crustal shortening in the form of initial flexure folding (shortening) must have occurred early during the F1 deformational event. Thus the shortening in the Eureka Syncline, to which a value of 36 per cent has again been ascribed, is assumed to have been approximately identical to that experienced by the formations in the vicinity of the Lily Mine. The initial shortening deformation of the Eureka Syncline was later augmented by a flattening deformation which resulted in the production of a massive "similar" fold.

It was shown earlier that the total shortening in the mine area amounted to about 63 per cent. In much the same way then, the total shortening in the Joe's Luck - Sheba Siding area (where the pebbles were measured) amounted to 36% + (39% of 64%) viz., 61%. Because the amount of flattening obtained from the separate areas alone gave such a remarkable correspondence of values and because it could be shown with certainty that the mine area had undergone initial flexure folding (shortening) then, by analogy, a final conclusion that can be drawn from the data suggests that both areas underwent approximately identical amounts of compression derived essentially from the intrusive phase of the Nelspruit Granite.

GENERAL DISCUSSION

The method described by Ramsay (1962) for calculating quantitatively the amount of fold deformation assumes that throughout the area where measurements have been made the flattening has been uniform. It is also assumed that there is no significant change in the "b" dimension in the strain ellipsoid with axes a, b, and c.

From the measurements of the pebbles it can be seen that only a relatively small amount of change took place in the B (intermediate) dimension in the strain ellipsoid with axes A, B, and C.

In the investigation, only the effects of flattening have been dealt with whereas the effects of shearing have been disregarded. The results, due to their close correlation, indicate that in cleavage folding ("similar" folding) the principle deformation may be solely due to flattening, i.e., once the buckling of a rock unit has reached a stage corresponding to the last limits of flexure folding, the remaining deformation may, in some cases, comprise only flattening of the fold.

This study also confirms the findings of Ramsay (1962) who maintained that flattening was a dominant mechanism in the production of "similar" folding. The amount of flattening of the mine folds was derived from data that plotted along a curve signifying the previous existence of flexure folding. Had the data plotted in any other manner the earlier shortening by flexure could not have been established. The production finally, of the "similar-type" folds can only be explained by additional flattening of the formations.

The pebble and fold occurrences in the Joe's Luck Siding - Sheba-Eureka Siding areas and the Lily Mine area probably represent a rare opportunity in which to study the extent and style of deformation suffered by rocks that have undergone compressive stresses.

Although the number of pebbles and folds measured were limited in that this was by no means an attempt to exhaustively investigate their relationships, the results do, never-the-less, conform very favourably to some system; this after taking cognizance of the experience and empirical knowledge at present available.

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Acknowledgements

The author wishes to express his thanks to M.J. Viljoen for permitting pebble deformation values, obtained from the Joe's Luck Siding area, to be incorporated in this paper.

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Key to Figures

PLATE 1

Figure 1 Flattened conglomerate pebbles from the basal conglomerate of the Moodies Series in the Eureka Syncline. Photograph shows the a/b planes of chert pebbles. Locality, Sheba Siding.

Figure 2 Flattened conglomerate pebbles showing the a/c planes. Note the buckled and twisted nature of some of the pebbles. Locality, Sheba Siding area.

PLATE 11

Figure 3 Tight isoclinal fold in Fig Tree shales. Locality, 70 Foot Level, Lily Mine.

Figure 4 Tight isoclinal folds with narrow wave lengths and large amplitudes. Locality, Fig Tree shales - 2 Level cross-cut Lily Mine.

Figure 5 Graph showing the relationship between t'' = (measurement of t' where bedding dips at α'/ measurement of t' at fold hinge) and α' with variable amounts of flattening (x).
The heavy dots represent data from the fold shown in Figure 4; the crosses, data from the fold illustrated in Figure 3. (Graph after Ramsay, 1962).

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PLATE 1

Fig. 1

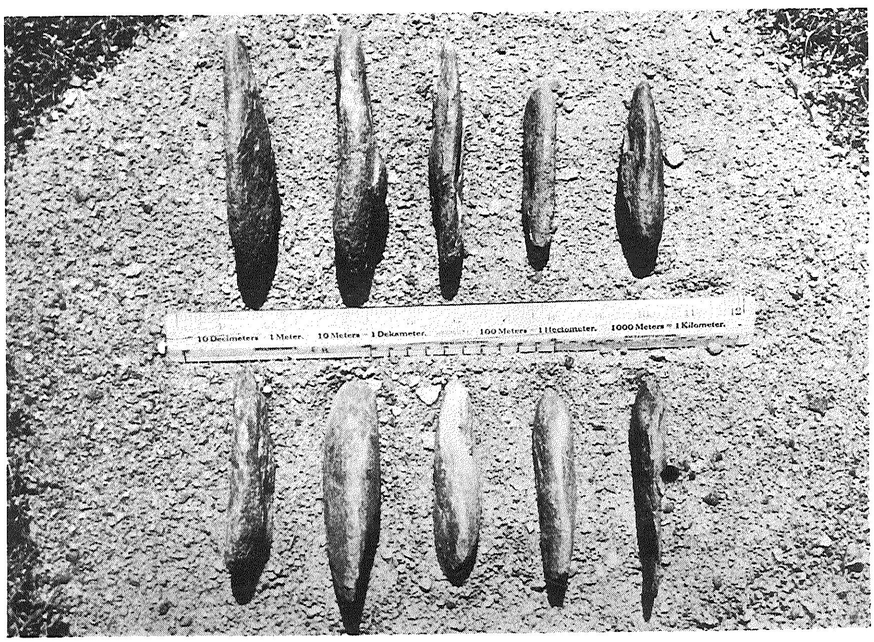

Fig. 2

PLATE 2

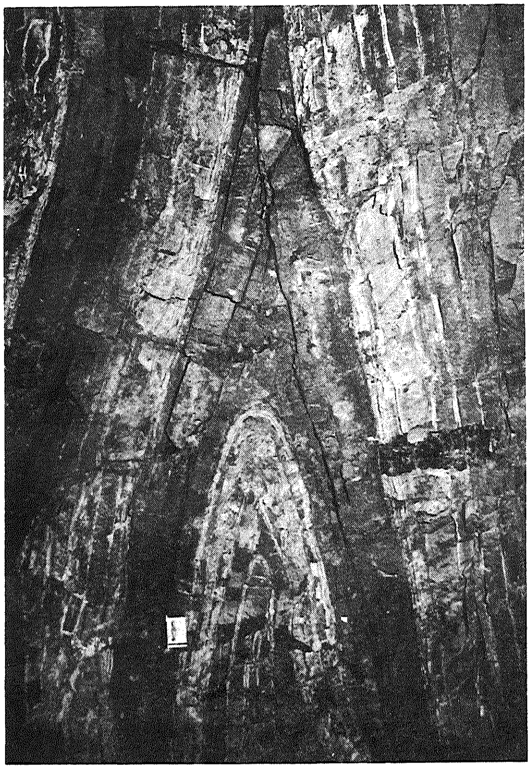

Fig. 3

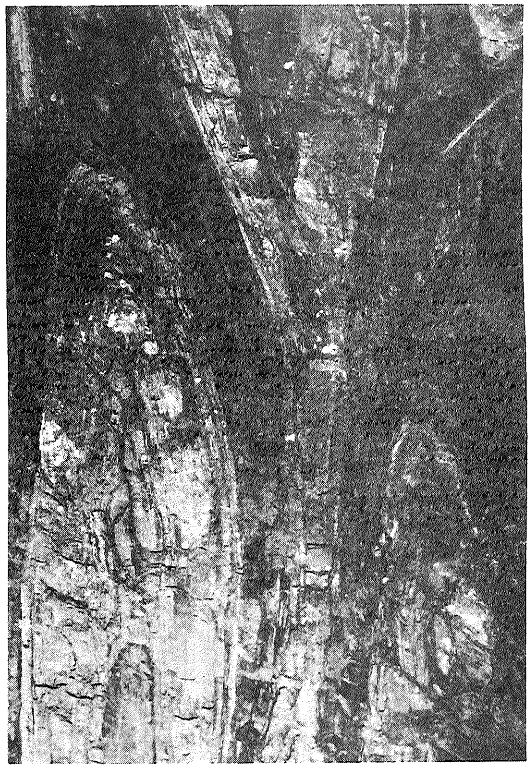

Fig. 4

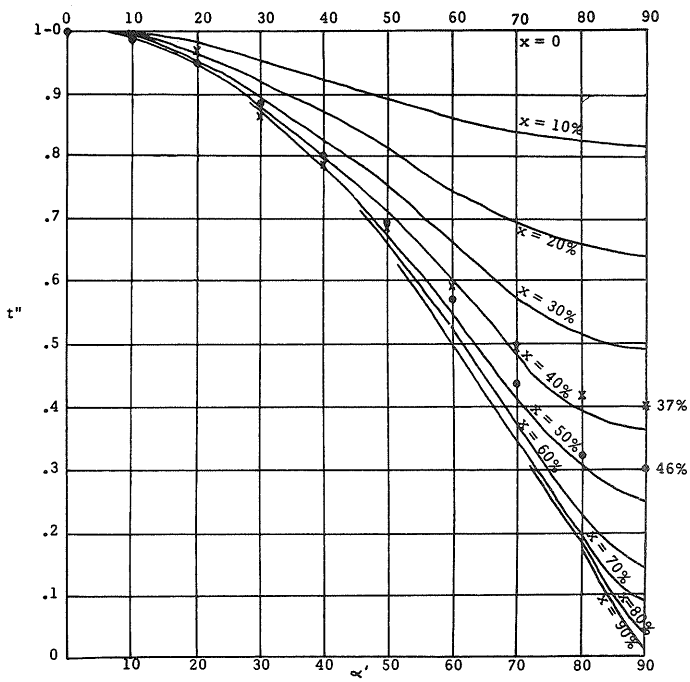

Fig.5