

Sedimentary studies in the Nappe de
la Breche, French Prealps

by

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October, 1969.



A B S T R A C T.

The sequence of rocks studied* is divided into the following units on the basis of texture and mineralogy:-
(1) Lower Breccia Formation (Breche Inferieure) - breccia facies; (2) Lower Breccia Formation - flysch facies; (3) Upper Shales (Schistes Ardoisiers) Formation; (4) Upper Breccia (Breche Superieure) Formation.

Variation in thickness of the breccia facies of the Lower Breccias, thickness of individual beds, proportion of breccia in the succession, and maximum phenoclast size indicate a source area to the north and west. The breccia facies of the Lower Breccia passes in a south-easterly direction to the flysch facies and then into the Lower Shales (Schistes Inferieurs) Formation. There is also an upward passage from the Lower Breccia, breccia facies to the Lower Breccia flysch facies. Breccias in the breccia facies are believed to have been transported as inertia clast flows, and after deposition their uppermost parts were reworked by bottom currents. Breccias occur in the flysch facies but sand-grade beds are more common. The sand-grade beds (calclithites) are commonly graded and were deposited by turbidity currents. The calclithite turbidites are often coarse and sometimes contain dune structures. These dunes are similar to those in the limestone member of the Whitehouse Formation (Ordovician) at Girvan, Scotland. Their formation is believed to depend principally on the availability of granule-pebble material, and they are indicative of a proximal turbidite environment. Also found in the turbidites

* (Jurassic - Cretaceous)

is a repetition of several divisions of parallel lamination, and current-ripple lamination. This feature, which also occurs in the limestone member of the Whitehouse Formation at Girvan, indicates that internal structures in turbidites do not always represent a simple decrease in flow power. Grain size distribution in, and rate of deposition from, a turbidity current are cited as important factors in determining the final sequence of internal structures in a turbidite. The influence of rate of deposition on development of a preferred orientation of elongate grains is demonstrated with reference to two graded calcilithite beds.

The flysch facies of the Lower Breccia Formation passes upwards into the Upper Shales Formation, where breccias are scarce but still of the Lower Breccia-type. Here, shales and mudstones predominate, and the thickness variations suggest existence of a south-west to north-east rise in the centre of the basin. At some parts of this rise, there was no deposition of the Upper Shales.

With cessation of deposition of the Upper Shales, coarse breccias appeared again. These breccias contrast strongly with those of the Lower Breccia. They have up to 40% calcareous mud matrix, and are well-graded. A mud flow origin is suggested. Occasional irregular distribution of matrix, 'clouds' of fine breccia in coarse, and slabs of breccia in the interbedded limestones indicate cohesive behaviour in some cases. The source for these breccias was to the north and north-west.

Palaeocurrent indicators are few. The bottom currents which reworked parts of the Lower Breccia, breccia facies - breccias were variable in direction but fitted into the submarine fan environment which is envisaged for these rocks. In the flysch facies of the Lower Breccia a few sole markings and dune structures indicate a more or less west to east dispersal, while directions obtained from current ripple cross lamination show wide variation, particularly in the thinner beds. This variation is interpreted as a result of deposition from thin turbidity flows passing over an irregular bottom, but some reworking by indigenous currents cannot be ruled out. There was no bottom current action during deposition of the Upper Breccia Formation.

The lithologies throughout the sequence reveal a source area of predominantly carbonate rocks. The appearance of metamorphic rock fragments at the top of the Lower Breccia indicates penetration of the sedimentary cover, but their relatively small proportion shows that exposure of metamorphic terrain was not extensive. During Upper Breccia times a significant contribution was made by the supply of bioclastic material and lime mud presumably from the littoral region. Rounding of clasts is generally poor and indicates no extensive working of the material by currents.

The sediments were deposited in a near-source environment by inertia clast flows, turbidity flows, mud flows, and slides. Some reworking by bottom currents took place in the lower part of the succession, but introduction of the material by bottom currents is not considered likely. The source area

was undergoing uplift. Erosion, transport, and deposition were rapid. A likely original site of deposition is about 100 km to the south, at the northern margin of the Piemont Trough, during Jurassic and Cretaceous times (Trümpy 1955), with the adjacent Briançonnais Cordillera providing a nearby source area. This suggestion is endorsed by the present author, in light of the results of this study.

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I. INTRODUCTION.

The aim of the present study is to describe a sequence of coarse clastic deposits which are believed to have formed at or near the scarp of a submarine-fault-zone, with a view to suggesting their modes of transport, dispersal and deposition.

The rocks in question occur in the Breccia Nappe (Nappe de la Breche), one of the Pre-alpine nappes on the north-west front of the Alpine chain. The nappe forms a SW - NE trending massif in Haute Savoie and Switzerland, to the south of the Lake of Geneva (FIG. 1). The area studied is in the south-east, French, part of the nappe, from the region of Pic de Marcellly to the Franco-Swiss Frontier. The area is covered by the Carte de France 1:50,000, feuille XXXV-XXXVI-29, Sambens-Pas de Morgins, issued by the Institut Geographique Nationale, Paris.

The section studied extends from the base of the Lower Breccia Formation to the top of the Upper Breccia Formation (FIG. 2). A lack of diagnostic fossils makes accurate stratigraphy impossible, but approximate ages are given on FIG. 2 (after Lugeon 1896; Schroeder 1939; and Chessex 1959).

The sediments of the nappe are believed to have formed on the southern side of the Brianconnais Cordillera in Jurassic times, near to the then active fault-scarp dividing the cordillera from the Piedmont Trough (Trumpy 1955, 1957 and 1960). The rocks have therefore suffered a displacement of about 130 km northwards from their original site of deposition.

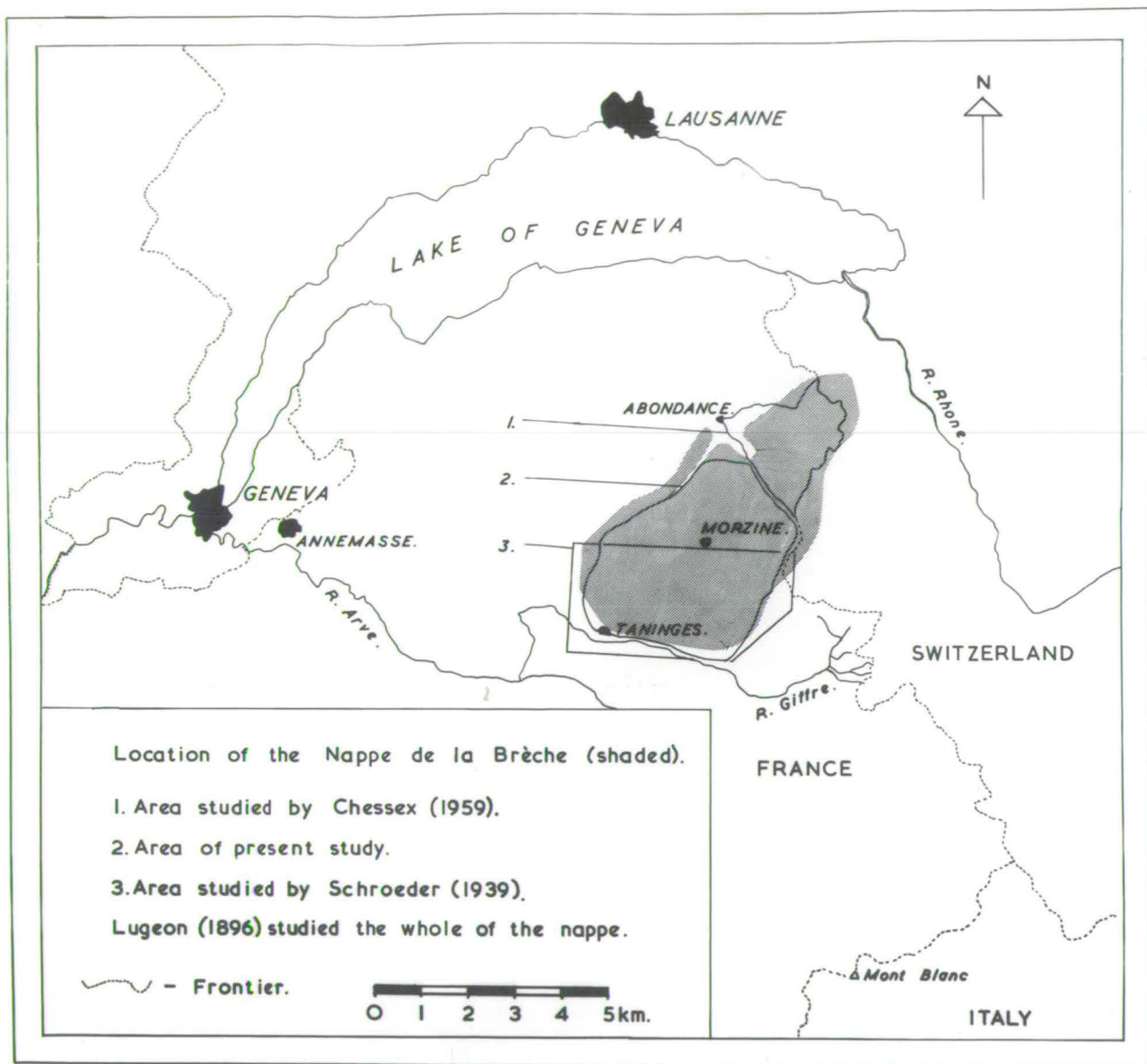


FIG. 1. Location of the Nappe de la Breche.

The rocks of the nappe have been relatively little deformed. In the extreme north-east (Hornfluh region) (Arbenz 1947), metamorphism has occurred, but in the area of the present study there has been no metamorphism, and the folding is of a large-scale, open type. The strongest effect of the deformation is a poorly developed fracture-cleavage in the shales and mudstones of the Upper Shales (Schistes Ardoisiers).

(1) Previous work.

Lugeon (1896) was first to describe the area, and he set up the main stratigraphic divisions. He suggested that the breccias may have formed by a slide or mud flow mechanism.

Geographical variations in bed thickness and grain size of beds led Schroeder (1939) to postulate the existence of a cordillera to the north and west of the original position of sediment-accumulation. Formation of the breccias, often with graded bedding, he ascribed to slides.

A slide origin for the breccias with the thinner bedded sand-grade deposits a result of deposition from turbidity currents was suggested by Kuenen and Carozzi (1953), but turbidity current action was considered subordinate by Trumpy (1955, 1957) and by Chessex (1959). Chessex (1959) thought mud flows and slides were the principal transport and depositing agents. Initiation of the slides has been ascribed to earthquakes (Schroeder 1939), or to overloading of material causing instability on steep slopes (Arbenz 1947). The non-chaotic aspect of the breccia beds has been noted as strange for deposits

AGE	THICKNESS	FMN.	DESCRIPTION	
EOCENE PALEO-CENE U. CRET. L. CRET.	> 400 m	FLYSCH "Mesocretaceous"	Calc. ssts., lsts., and shales. Some volcanics near base. Limey ssts. with micaceous shs.	
UPPER JURASSIC	0 - 200 m	BRECHE SUPERIEURE	Muddy carbonate breccias, calcilithites, and micritic lsts.	
UPPER JURASSIC	0 - 300 m	SCHISTES ARDOISIERS	Red and green silty mudstones, with siltstones, fine ssts., dark gray shales, and a few breccias.	
MIDDLE JURASSIC	0 - 1300 m	BRECHE INFERIEURE	Alternating, breccias, calcilithites, calc-siltstones, and shales. Thick, coarse, carbonate, breccias.	
LOWER JURASSIC	0 - > 500 m	SCHISTES INFERIEURS	Black calc. shales and limestones with some fine grained breccias.	
<p><i>This is an idealized section. Formation boundaries are not, in fact, clearly cut, and are probably diachronous. A paucity of fossils makes the stratigraphy approximate.</i></p>				

FIG. 2. Stratigraphic section showing the rocks studied. In the text the names have been anglicized as follows: Schistes Inferieurs - Lower Shales; Breche Inferieure - Lower Breccia; Schistes Ardoisiers - Upper Shales; Breche Superieure - Upper Breccia.

which had presumably accumulated at the bottom of a steep slope (Tercier 1947).

Variations in lithology throughout the succession suggest that there was erosion down through a sedimentary cover of limestones, dolomites, and sandstones, to underlying mica, chlorite, and garnet schists (Schroeder 1939).

Fossils are scarce in the sequence. There are however trace fossils, in the form of grazing trails and some burrows, at the tops of graded calcilithites in the flysch facies of the Lower Breccia. Pentacrinus tuberculatus Miller, from the lower part of the Lower Shales indicates that this is Lower Lias, (Schroeder 1939). Calpionella elliptica Cadisch, and Calpionella alpina Lorenz in the Upper Breccia indicate an Upper Jurassic (Tithonian) - Lower Cretaceous (Barremian) age (Schroeder 1939).

Those fossils which have been found, and other radiolaria remains indicate a marine environment.

II. LOWER BRECCIA.

In this study, the Lower Breccia Formation has been divided into two parts on the basis of field evidence:-

2. An upper part of breccias, calcilithites, and calcareous pelites. The breccias are seldom coarser than pebble grade, and the majority of the beds are graded calcilithites of sand and silt grade - this is the Flysch Facies.
1. A lower part composed almost entirely of breccias, all granule grade or coarser. There are almost no calcilithites or shales. This is the Breccia Facies.

In the sequel, these two facies shall be considered separately.

(1) Breccia Facies.

1. Development and distribution.

The breccia facies comprises thick (up to 30 m) beds of breccia with grain size from coarse sand to boulder grade. Associated sand beds are minor in amount. Individual breccias are generally broadly lensoid in shape and may extend for up to 3 km in a south-west to north-east direction, i.e. parallel to the presumed coastline. They are composed mainly of poorly sorted, poorly rounded, dolomite, limestone, quartzite, and shale phenoclasts of presumed Triassic age (Schroeder 1939, Chessex 1959) and have no mud matrix. They are often lacking in internal structures, but may show parallel or cross-bedding, and may be poorly graded. They overlie the Trias at Col de la Ramaz (Schroeder 1939) but elsewhere they succeed the rocks of the Lower Shales. Their upper limit is marked by the sudden decrease in number of very coarse boulder breccias and the in-

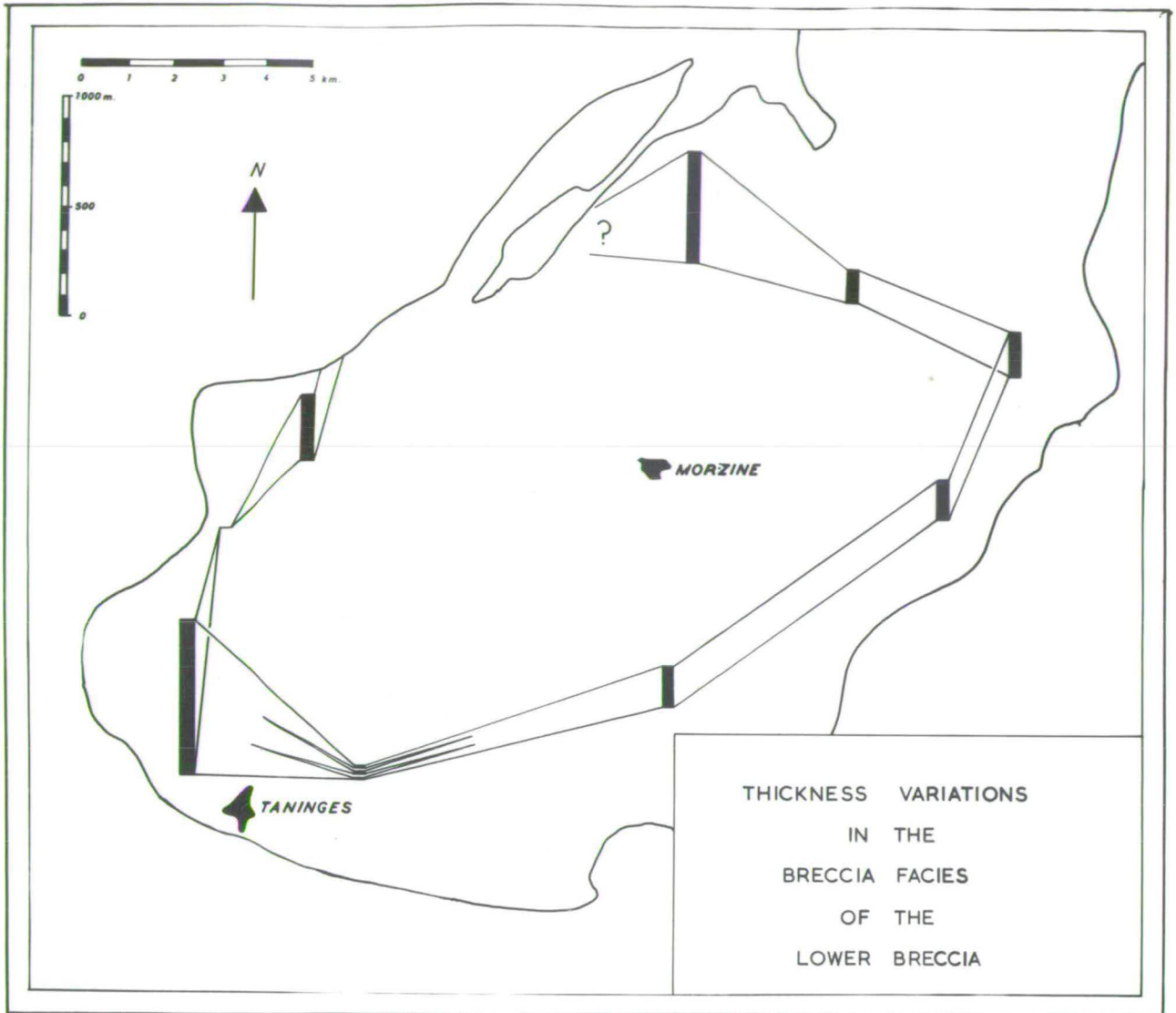


FIG. 3. Areal thickness variations in the breccia facies of the Lower Breccia.

coming of numerous sand-and silt-grade calcilithites (see description of flysch facies - p.32).

The breccia facies is not developed uniformly over the whole nappe (FIG. 3). Lugeon (1896) noted a general eastward thinning of the whole of the Lower Breccia (i.e. breccia facies + flysch facies of the present study), and suggested a westerly origin. Similarly, Schroeder (1939) - see area in FIG. 1 - suggested an origin to the north-east, west, and south-west at different localities. Chessex (1959) in the north-east part of the nappe (outside the present area, see FIG. 1) suggested a north-west origin.

The present study reveals thickness variations similar to those found by Schroeder (1939), with additional data from the Roc de Tavaneuse - Avoreaz region, (see FIG. 4 - locality map). The breccia facies shows maximum development at Pic de Marcelly and Roc de Tavaneuse, with thinning to the north, east, and south-east at the former locality, and to the south-east at the latter (FIG. 3). To the north-east of Roc d'Enfer, the Lower Breccia Formation has been cut out by the basal thrust plane of the nappe, so it is impossible to say whether or not there was thinning here. However, between St. Jean d'Aulph and Roc de Tavaneuse, the absence of the Lower Breccia scarp, which is elsewhere very prominent, suggests that thinning is a possibility. Thus, there is thinning away from Praz de Lys in a radiating direction, and thinning from Roc de Tavaneuse is to the south-east and possibly the south-west. Assuming that thinning was away from source, and that the nappe has suffered

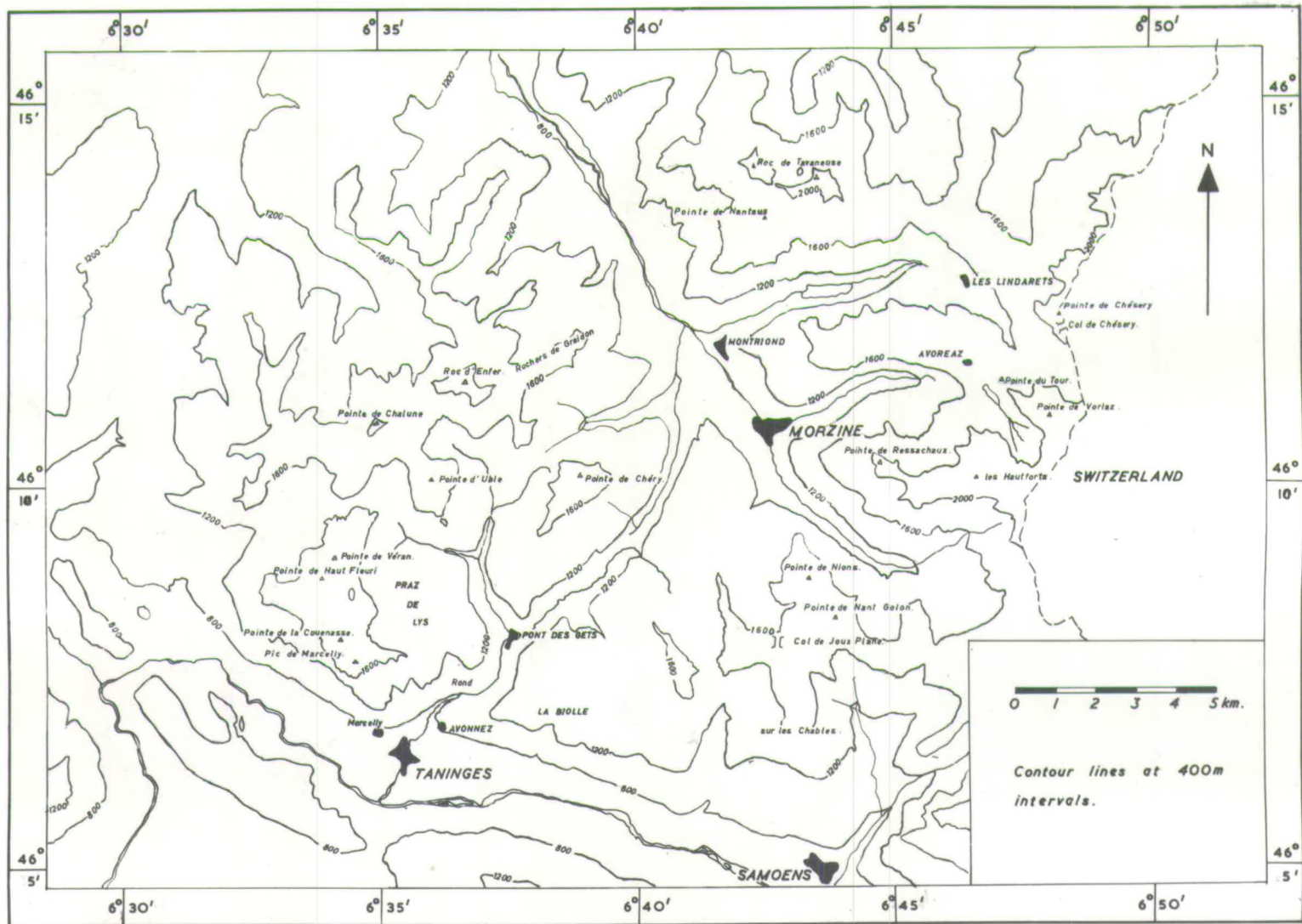


FIG. 4. Map of localities in the area.

little rotation about a vertical axis during carriage from its initial site, the source area for the breccias appears to have been towards the north and west of the original depositional area. The location of the thickest piles of breccia at Praz de Lys and Roc de Tavaneuse suggests that supply may have spread out from these localities as large submarine fans. Schroeder (1939) remarked on the similarity of the shape of the Lower Breccia Formation to a large alluvial fan. There is also the possibility that the small wedge of breccia around Roc d'Enfer represents a small fan between the other two.

As well as the essentially lensoid nature of some parts of the breccia facies (at Pic de Marcelly it is 600 m thick but it thins in a north-westerly direction to zero in about 3.5 km) there is a facies change to a sequence with more finer, thinner beds. This second change is well seen if the breccia facies is traced from the steep west slope of Pic de Marcelly, in an east-south-easterly direction, to the steep slope south of La Biolle, where breccias still occur but are fewer in number and are interbedded with graded calcilithites and calcareous shales.

2. Bedding thickness.

Individual breccia beds may be as much as 3000 cm thick, with a lower thickness limit of about 100 cm, and a few cases as thin as 50 cm (FIG. 5). Single beds are bounded at their upper and lower surfaces by an erosion surface, or an erosion surface accompanied by a change in texture. In general, the uppermost part of a bed is finer than the main part of the bed.

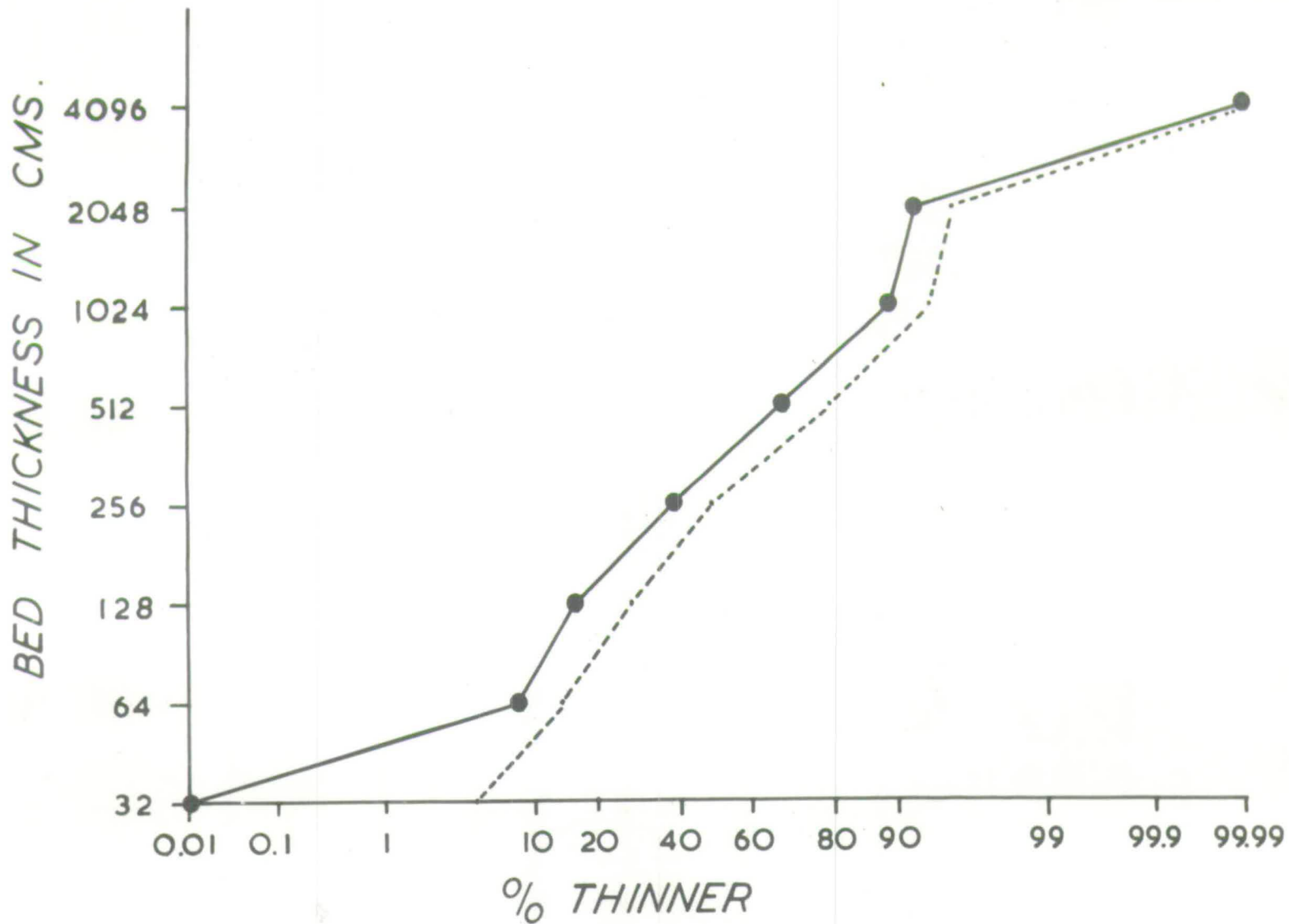


FIG. 5. Thickness/cumulative frequency distribution for breccias of the breccia facies (solid line), and for the whole of the Lower Breccia Formation (dotted line).

The transition from the main, usually massive, part of the bed to the upper finer part, may be either slow or rapid, but is never marked by a bedding plane. On the other hand, the junction between the fine-grained top part of one breccia and the base of the overlying one is almost always marked by an erosion plane - if it is not then the change from one to the other is abrupt rather than transitional.

Variation in bed thickness for the breccia beds of the breccia facies is not very striking when histograms of bed thickness at different localities are considered (FIG. 6). This is a result of small sample size at each locality. However, if the maximum, or average (arithmetic mean), bed thickness of the breccias at each locality is considered (FIG. 7), a pattern of dispersal from a westerly direction in the south-west of the nappe, and from a northerly direction, in the north-east of the nappe is suggested. This is similar to the results obtained from the consideration of thickness variations of the breccia facies as a whole. Both Schroeder (1939) and Chessex (1959) reported a marked decrease in thickness of individual beds (accompanied by a decrease in clast size) from south-west to north-east, and from west to east, indicating a source to the west and south-west. However, there are two points worthy of consideration here:-

1. The actual areas studied by both Schroeder (1939) and Chessex (1959) do not include the area around Roc de Tavaneuse, and the evidence from this part is critical in the present interpretation. Chessex (1959), in the

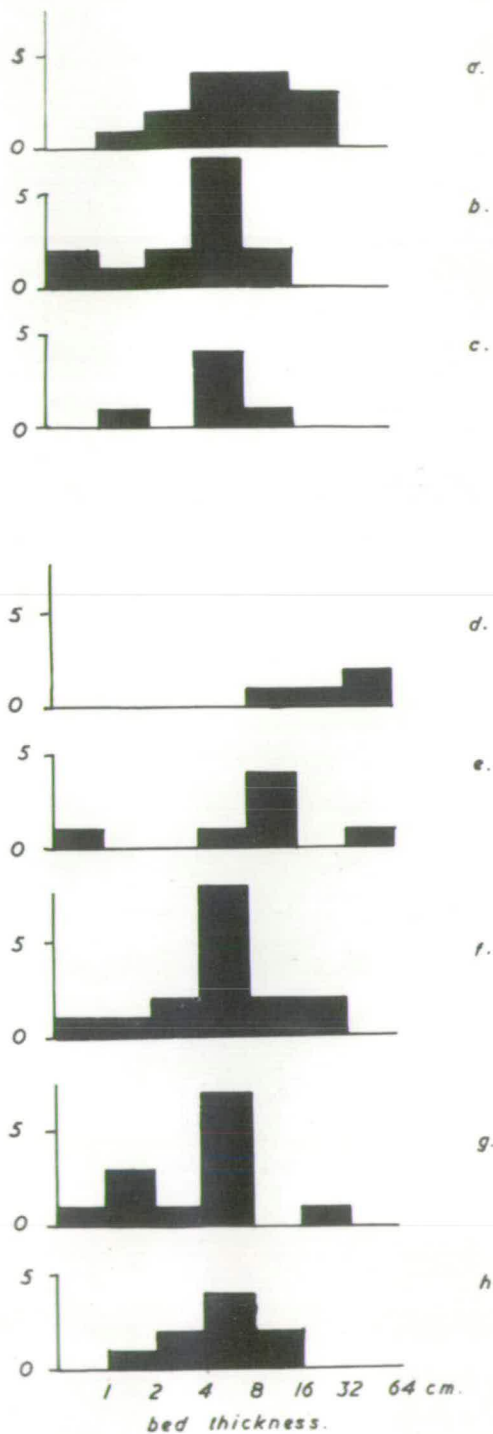


FIG. 6. No.frequency/breccia thickness histograms for different localities, breccia facies, Lower Breccia. a-Praz de Lys; b-Rond; c-la Biolle, d-Roc de Tavaneuse; e-Ardent; f-Col de Chesery; g-Avoreaz; h-Col de Jouplane.

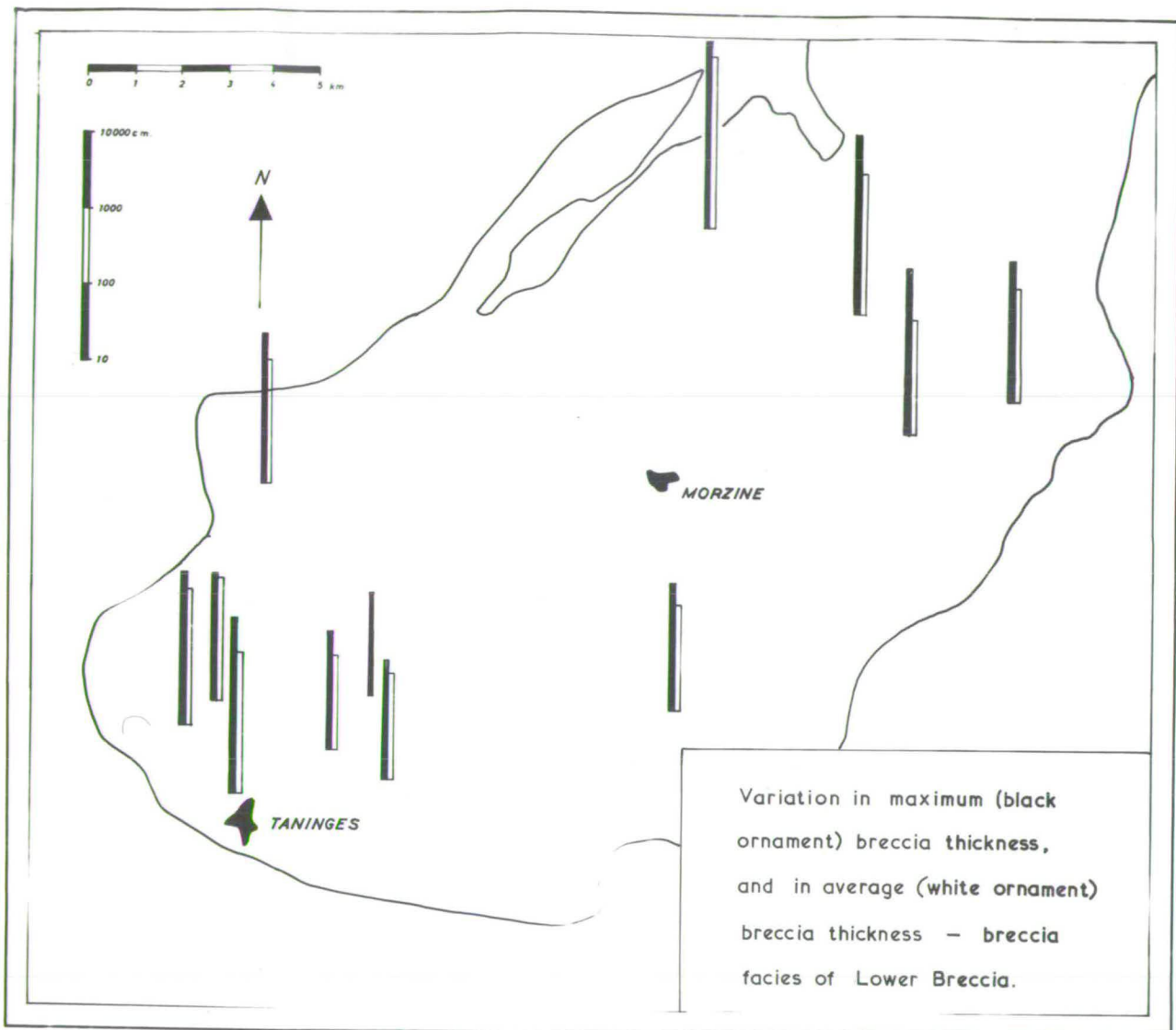


FIG. 7. Maximum breccia thickness (black), and average breccia thickness (white), at different localities, breccia facies, Lower Breccia. At one locality only two beds were measured, so the average is not given.

area to the north-east of Roc de Tavaneuse, also found thinning of the formation to the south-east. The present work has shown that this thinning is repeated from Roc de Tavneuse to Avoreaz.

2. In both these cases (Schroeder and Chessex) the Lower Breccia was considered as a whole, whereas in the present study it has been considered as two separate facies, and for the breccia facies alone, the bed thickness variations suggest a fan-like dispersal. If there were two fans, then the major supply directions suggested by Schroeder (1939) and Chessex (1959), bearing in mind that they apply to the whole of the Lower Breccia, would fit into the pattern suggested here.

3. Clast size.

The largest clast I have seen in the breccias is of the order of 1500 mm, but a very large clast of 8000 mm x 2000 mm was seen in the Praz de Lys area by Schroeder (1939); further to the north-east Chessex (1959) has reported a maximum clast size of 1500 mm. Such clasts are not common with the average clast size rarely exceeding 500 mm diameter, and then usually in the thicker breccias. The majority of the breccias are pebble or cobble grade (FIG. 8), and it should be noted that they do not have any silt or clay matrix. The finest material present is coarse or medium sand and there is never sufficient to form a matrix for the breccias have a closed framework with all clasts touching.

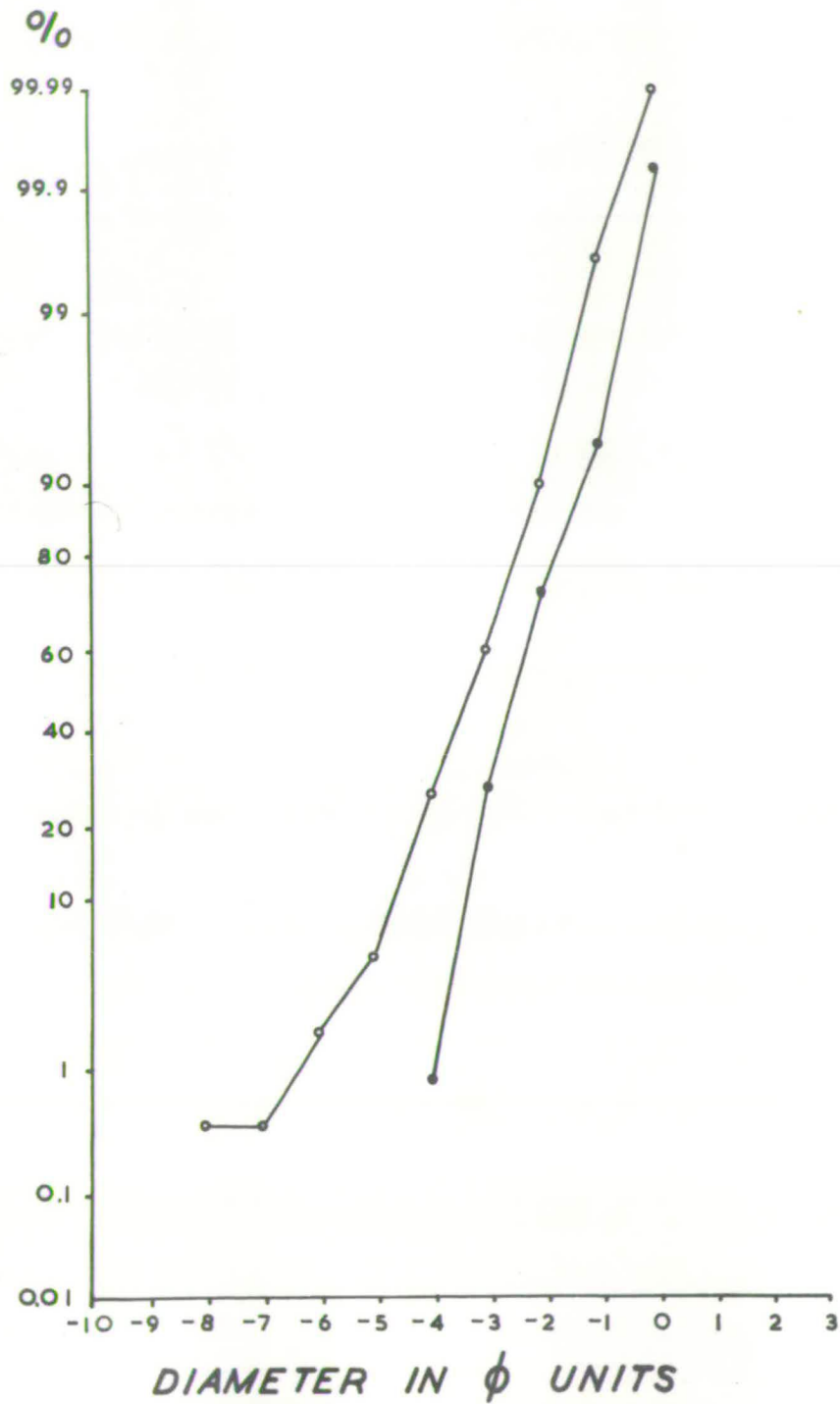


FIG. 8. Cumulative frequency/clast size curves for typical breccias, breccia facies, Lower Breccia, Praz de Lys. Open circles - graded breccia whole bed. Solid circles - cross-stratified part of a breccia.

The data are uncorrected and derived from point count analyses at the outcrop.

There are two types of variation in clast-size within the bed:-

1. Size grading from base to top.
2. Repeated units of different grain size which may, or may not, be graded.

The first type is dealt with below, page 13. The commonest occurrence of the second type is a topmost layer of gravelly-sand material overlying a main mass of a pebble, cobble, or boulder breccia with an abrupt contact between the two.

Alternatively, there may be a series of finer units at the top of a coarse breccia; these fine units are sometimes graded. Rarely, lenses of fine material occur within the coarser parts of breccia beds, as at Les Lindarets.

The largest clasts in a bed are found at or near the base, as shown by several breccia beds when clast-size is plotted against height above the base of the bed (FIG. 9).

4. Clast size and breccia thickness.

The correlation coefficient between clast size and bed thickness for the Lower Breccia breccias is low and significant at only the 10% level (FIG. 10). It shows that the quantity of material (bed thickness) deposited at a particular locality was related to the competency of the transporting medium - reflected in the maximum clast size present. A good correlation between clast size and bed thickness has been reported from graded sand beds (Scheidegger and Potter 1966) and from mud flows and cross-bedded conglomerates (Bluck 1967). A good

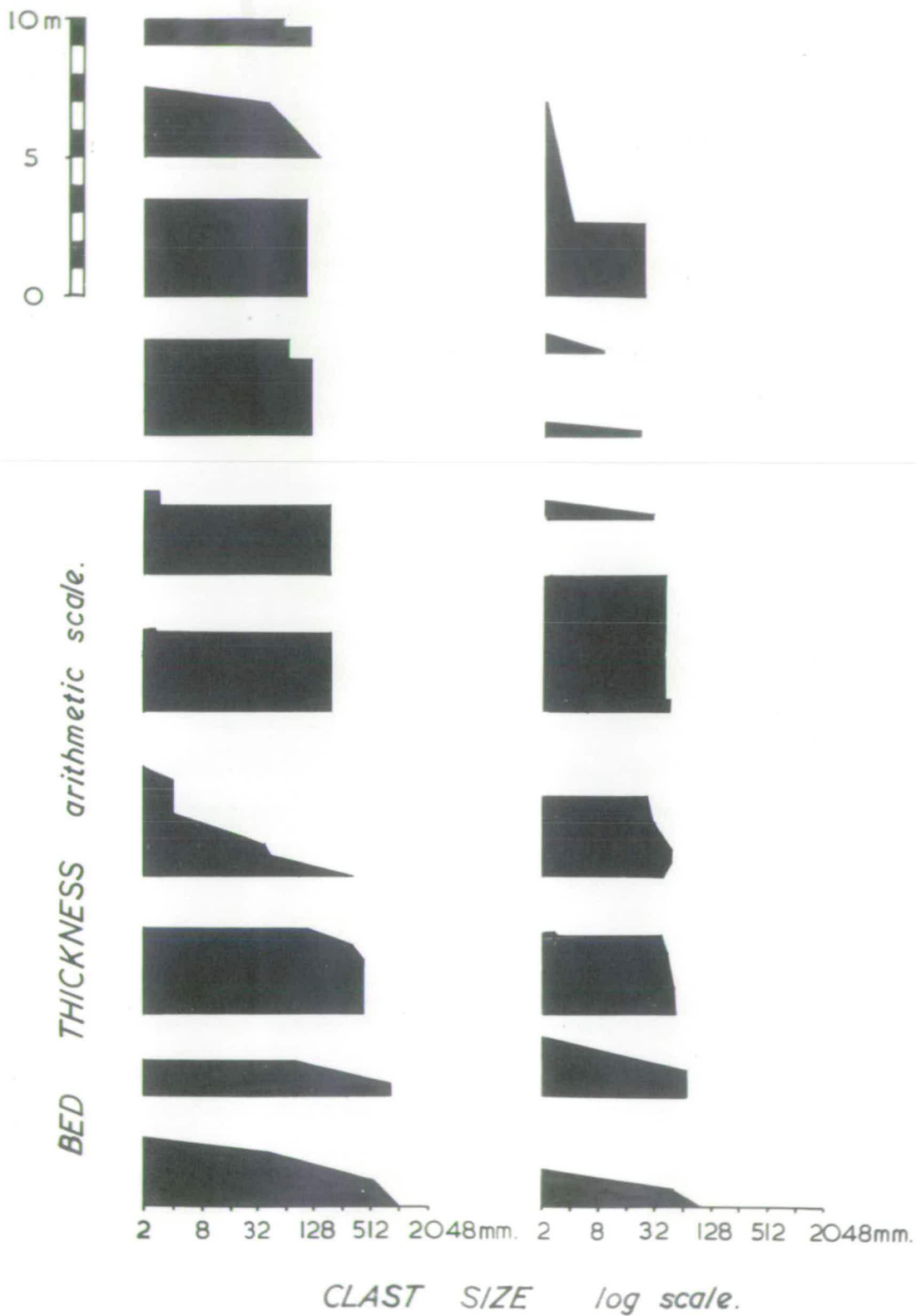


FIG. 9. Maximum clast size plotted against thickness for several breccia beds, breccia facies, Lower Breccia.

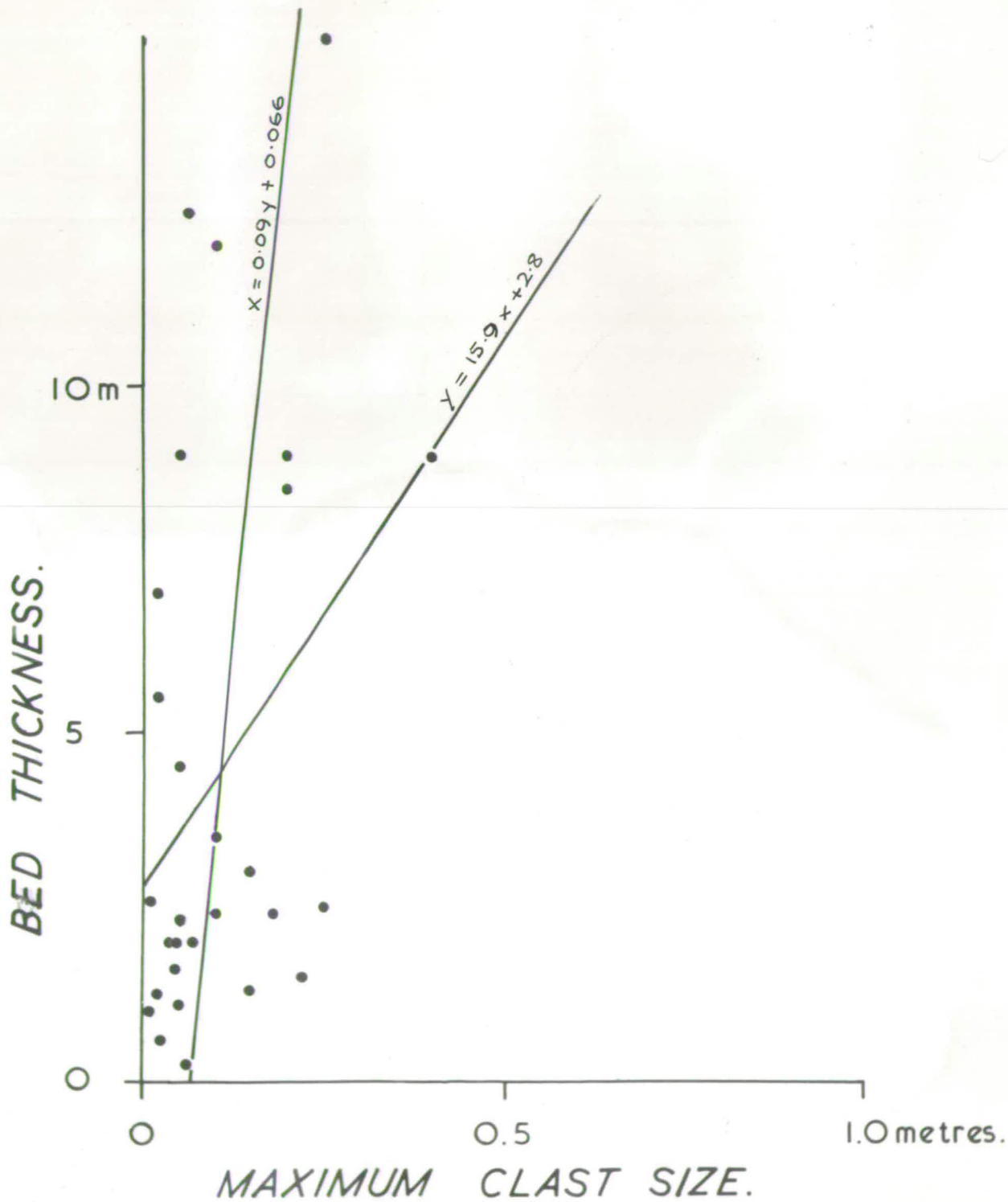


FIG. 10. Maximum clast size plotted against thickness for 28 breccia beds breccia facies, Lower Breccia.

correlation suggests deposition of the whole bed in one distinct episode.

No correlation at all would be produced in the case where current power was approximately constant and sediment supply was more or less unlimited, in which case, beds of any thickness could be built up regardless of clast size.

Even if deposition occurs in a distinct episode, departure from a good correlation may occur in one of the following ways:-

1. There may be an upper limit to the clast sizes available.
2. There may be addition or subtraction of material after initial deposition.

Field observations have shown that there is no indication of an upper size limit to the clasts available for the breccias. Addition or subtraction of material must take place by the operation of indigenous currents - this may be widespread or local depending on the range of currents which produce it.

The Lower Breccia breccias do not have structural or textural features throughout their thickness which suggest continued deposition from a fairly constant current, neither does the correlation coefficient, albeit low, favour such an origin. This, coupled with the large size of some of the clasts, and the tendency for sedimentary structures to occur only towards the tops of most of the beds, implies that the correlation may be explained by the relatively rapid deposition of the bulk of the bed - perhaps by a slide or flow.

The finer grained, often cross-stratified, upper parts of many of the breccia beds are considered to be the result of redistribution of finer sediment by indigenous bottom currents - redistribution rather than introduction because the finer parts of the breccias often grade down into the lower massive parts. Also, if the finer parts were introduced by bottom currents, then there was presumably ample opportunity for the build-up of much thicker deposits of such fine material, but no such deposits occur. So it is likely that redistribution of pebbles and gravel by indigenous bottom currents was an important factor in altering initial bed thicknesses. Thus a good correlation between maximum clast size and bed thickness, which would be expected in the case of a slide or flow origin, could be slightly modified by limited reworking of some of the material.

5. Geographical variations in clast size.

The average diameter of the ten largest breccia clasts seen at each locality reveals a pattern similar to that obtained for the geographical distribution of both maximum bed thickness and average bed thickness measurements (FIG. 11; see Pelletier 1958 and Scott 1966). There appear to be at least two main sources:-

- 1) To the north in the region of Roc de Tavaneuse.
- 2) To the west in the region of Pic de Marcelly.

Again there is the possibility that we are dealing with at least two submarine fans.

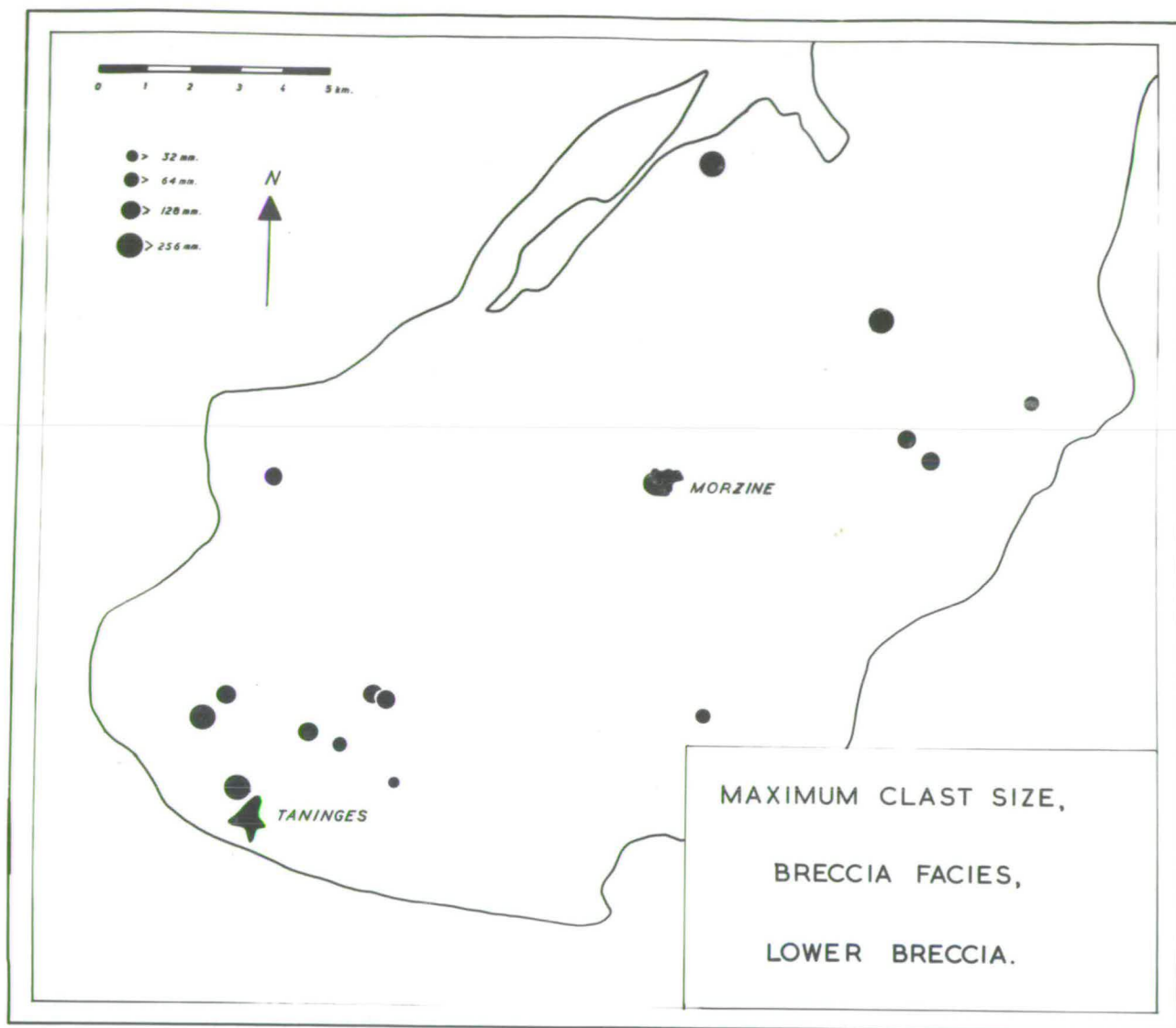


FIG. 11. Geographical variation in the average size of the ten largest clasts in breccias of the breccia facies, Lower Breccia.

6. Clast shape.

Clasts do not weather out of the outcrop, so, observations on clast shape are restricted to comments on the roundness as seen in section in the plane of the outcrop. In general, the clasts are poorly rounded. Analysis at two localities showed the modal class (Pettijohn 1957) to be 0.25 - 0.40 (FIG. 12), PLATE 1. The majority of the clasts in the breccia are limestone, dolomite, calcarenite, calc-siltstones, and calc-sandstones, with minor amounts of siliceous rock fragments.

The poor rounding of the clasts suggests that they were not for long exposed to abrasive processes. Kuenen (1956) showed experimentally that abrasion of pebbles on a pebbly floor is greater than on a sand floor, that abrasion on a pebbly floor increases with the square of the velocity, that increase of loss by abrasion is proportional to the pebble diameter, and that increase of loss by abrasion rises three to four times between fine and coarse gravel. The floor on which the breccias were deposited was certainly no finer than sand or silt-grade material, and was at times gravelly or pebbly. Also, pebble weight was generally large, with most of the breccia clasts coarser than gravel-grade - this would favour rapid rounding during abrasion. The inference is that these clasts have not suffered prolonged abrasion.

Since many of the clasts are limestone, if they had a subaerial origin, they have suffered little from chemical weathering. There is no evidence to show whether or not the

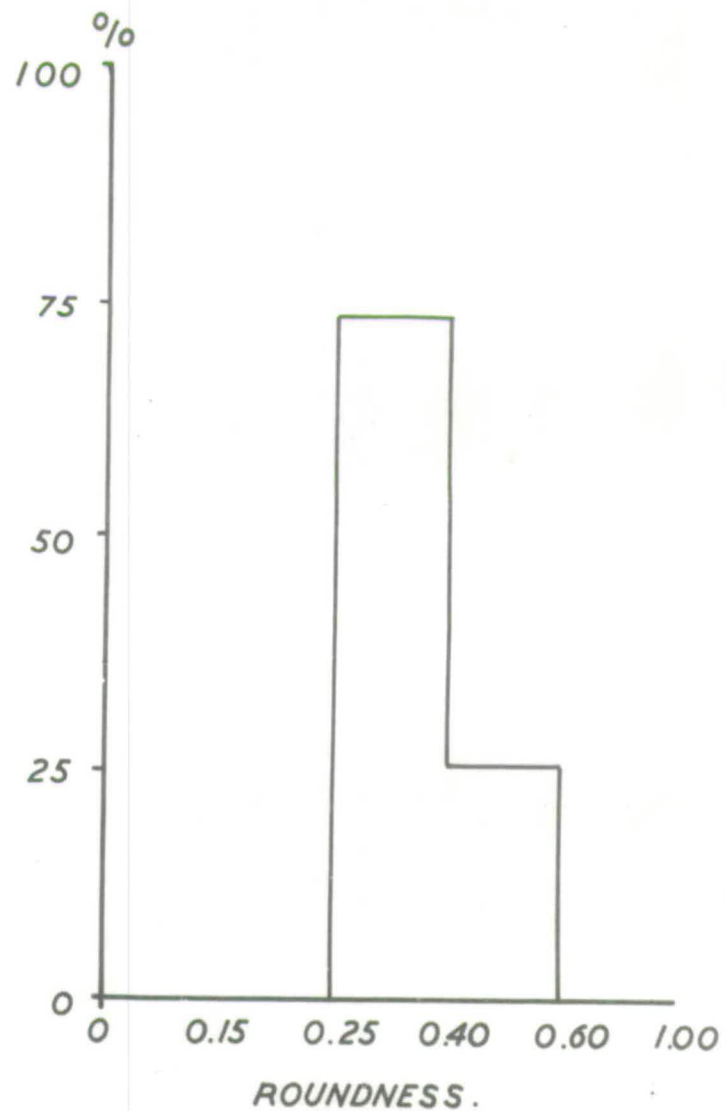
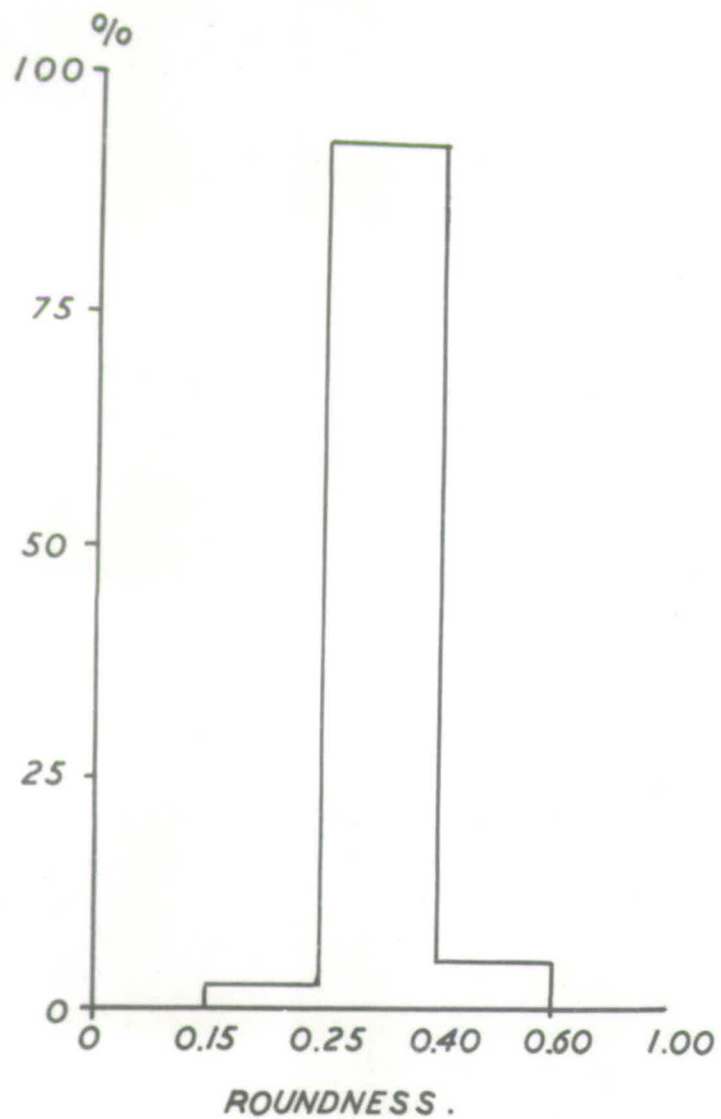


FIG. 12. Histograms showing roundness of 100 clasts in breccia beds at two localities, breccia facies, Lower Breccia.

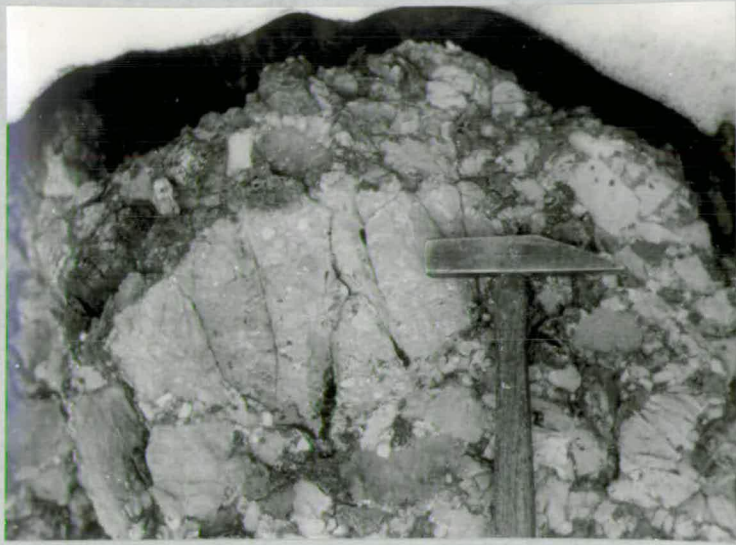


Plate 1. Breccia with poorly rounded clasts. Breccia
Facies, Lower Breccia, Pic de Marcellly.

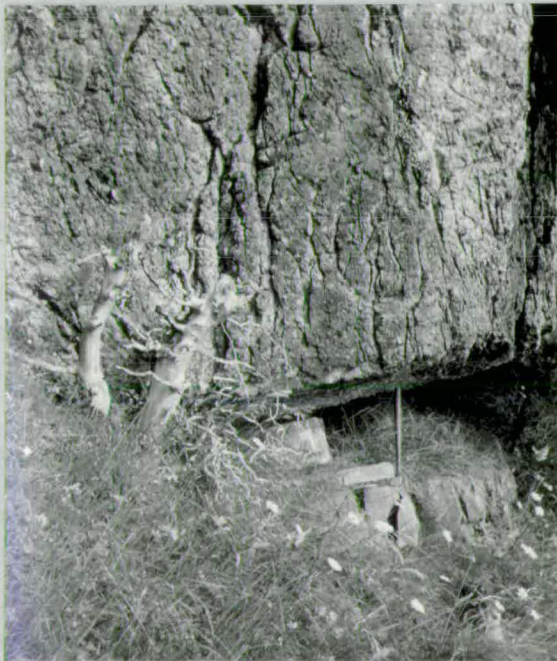


Plate 2. Very flat base of breccia. Breccia facies,
Lower Breccia, Les Lindarets.

clasts may have had a submarine origin.

The evidence suggests therefore, that the clasts have a nearby origin, are first-cycle rather than derived, were not much weathered at the source, and were not much abraded in the transport process.

7. Sedimentary structures.

a) Erosional sole features.

If the breccias do have a slide origin as suggested by Kuenen and Carozzi (1953), then it seems likely that erosional sole structures should be present in at least some cases.

Lower contacts of breccia beds with underlying beds are seldom exposed but when they are they are seen to be very flat, as in Plate 2 where a breccia with clasts up to 180 mm in diameter overlies a coarse sand-grade calcilithite with a very smooth contact. There are neither erosional nor load features. The only feature which suggests interaction between a breccia and the underlying bed is seen where a sandy, or at finest, silty, 'skin' from the top of a bed may adhere to the base of the breccia above (Plate 3) - but this is probably a direct result of the breccia settling into the underlying bed under its own weight.

No scour, tool, or load structures were seen at any locality in spite of the presence of pebbles, cobbles, or boulders at the bases of all beds.

b) Internal structures.

1. Clast size grading.

Many of the breccias show an abrupt, but marked, upward fining of clast sizes, while others show only slight variation in



Plate 3. Base of breccia showing silty 'skin' from top of underlying bed. Breccia facies, Lower Breccia, Pic de Marcelly.

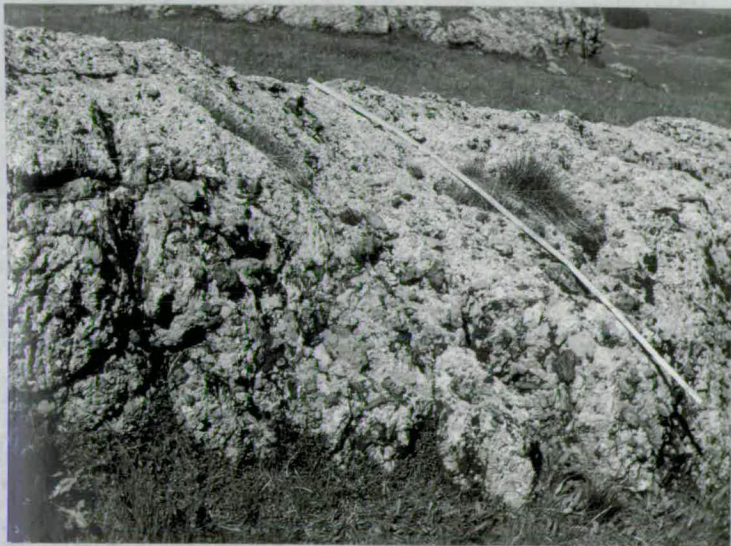


Plate 4. Clast size grading in breccia. Breccia facies, Lower Breccia, Praz de Lys. Each bar on scale is 20 cm.

clast size throughout, but appear to be graded from top to bottom. In one or two cases the grading is obvious (Plate 4), but in the majority it is difficult to appreciate in the field. To test for the presence of real grading in the breccias, an example from the Praz de Lys area (See Plate 5) was analysed using the method of Dahlberg and Griffiths (1967). The breccia which was analysed would not have been classified as 'well graded' in the field, nor did it show an abrupt change to a fine top. It was therefore important to decide whether or not there was any trend in clast size through the bed.

Procedure:- A grid, 2.1 m sq. was set up on the outcrop face. One direction of the grid was parallel to the bedding, the other perpendicular to it. The distance between the intersections was 300 mm, so that there were forty-nine intersections on the grid. The sizes of the five clasts nearest to each intersection were recorded. The raw data was converted to Phi units and the cumulative percentage distribution plotted (FIG. 8) - this showed that the Phi data had a normal distribution, i.e. the original data had a log-normal distribution.

The data was set out in matrix form and an Analysis of Variance performed. Rows of the matrix were parallel to the bedding, while columns were perpendicular to it. The Analysis of Variance gave the following results:-

<u>Source.</u>	<u>Variance Ratio.</u>	
Between Rows.	7.65	***
Between Columns.	0.95	N.S.
Row x Column Interaction.	0.77	N.S.

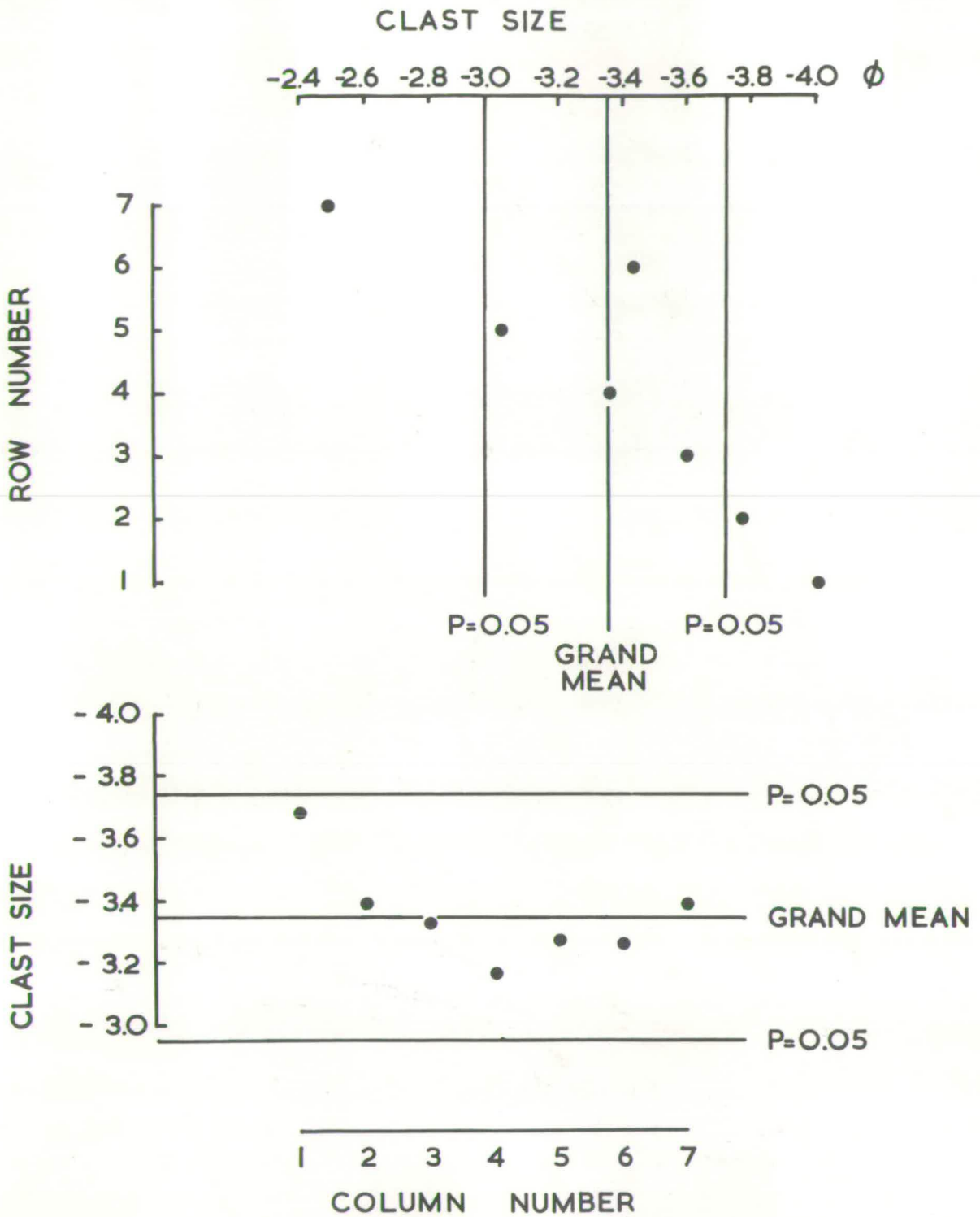


FIG. 13. Mean clast size in rows/columns for a breccia of the breccia facies, Lower Breccia, plotted in control chart form, with 5% probability limits indicated.

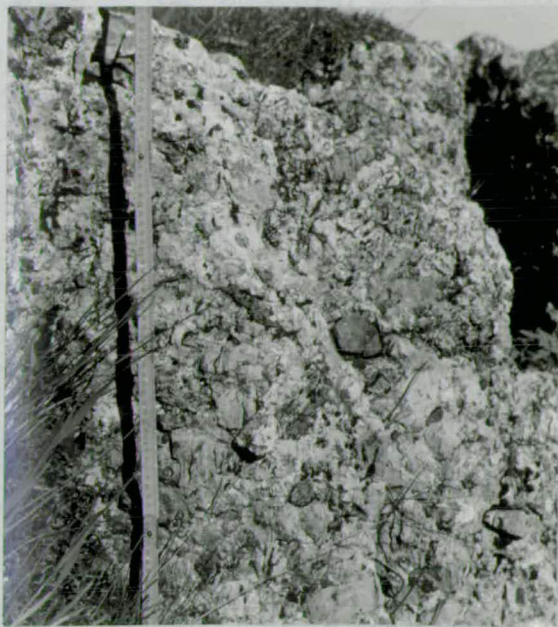


Plate 5. Breccia analysed for grading. Breccia facies,
Lower Breccia. Praz de Lys. Scale in cm.



Plate 6. Bedded top to massive breccia. Breccia
facies, Lower Breccia, Pic de Marcellly.

N.S. = not significant; *** = significant at the 0.5% level. Thus there is a variation in clast sizes, significant at the 0.5% level, in a direction at right angles to the bedding. Further, when the mean clast sizes for each row and column are plotted in control chart form, a trend in this between row variation is revealed (FIG. 13). Apart from the increase at row 6, there is a continuous, but slight (about 2 ϕ units range from bottom to top), grading through the bed.

2. Horizontal stratification.

Horizontal stratification is found at the tops of individual breccia beds. There are two types:-

- 1) A bedded top to a breccia, (Plate 6) within which a 'lamination' of type 2) may occur.
- 2) This is a smaller scale feature than 1) and is a result of the alignment of elongate clasts parallel to the bedding. The 'laminae' so formed are not of wide extent.

Laminations formed as a result of alternations of different grain-size do not generally occur. This stratification does not appear throughout the whole thickness of a breccia.

3. Cross stratification.

Cross stratification also, may occur at the tops of the breccia beds (Plate 7). The thickness of the cross-stratified units varies little, (FIG. 14), but there is a correlation, significant at the 5% level, between thickness and the maximum clast size (FIG. 15).

The breccia cross-stratification is usually of the α -type (FIG. 16 and Allen 1963) although some β -types also occur

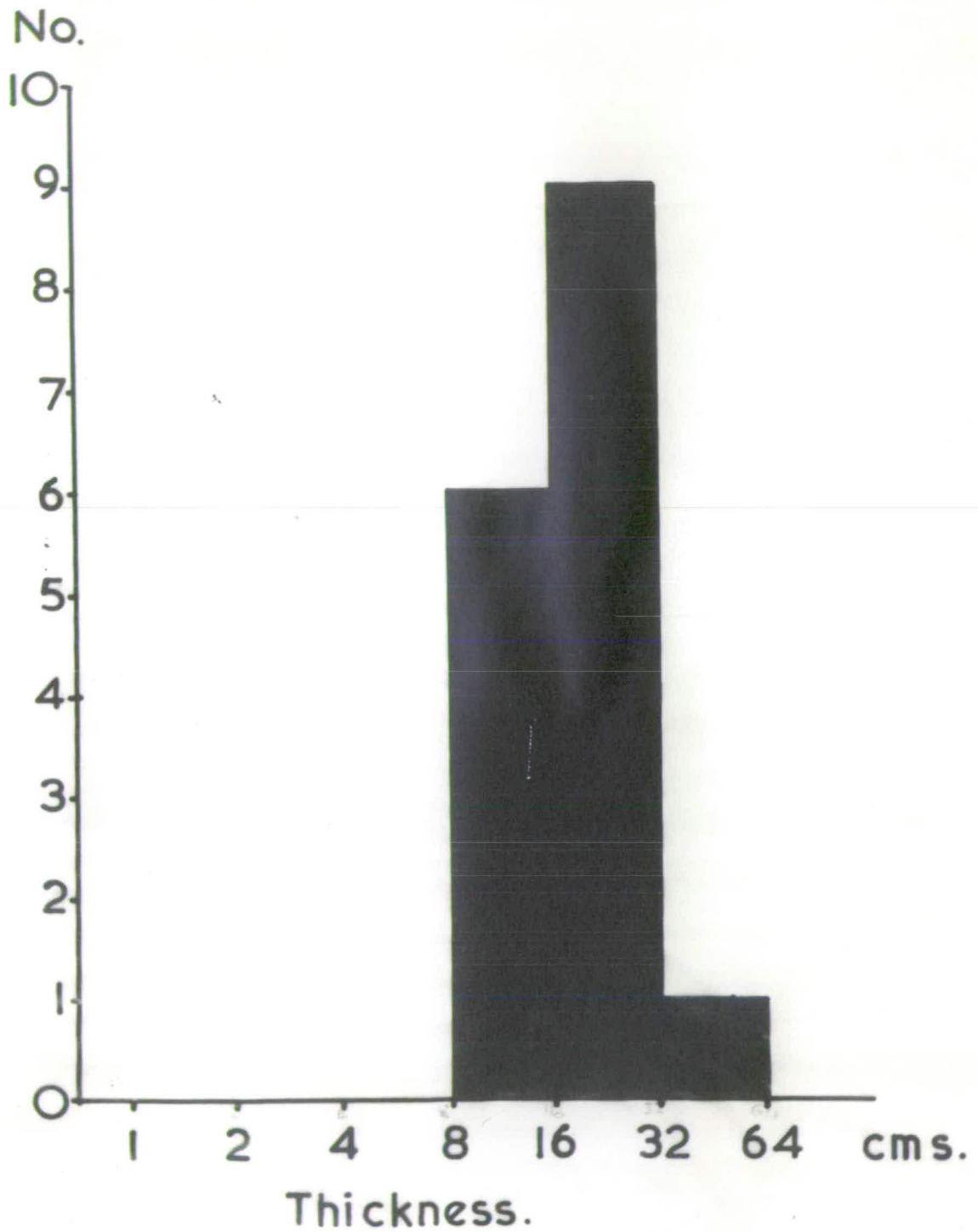


FIG. 14. No. frequency/thickness histogram for cross-stratified parts of breccias, breccia facies, Praz de Lys.

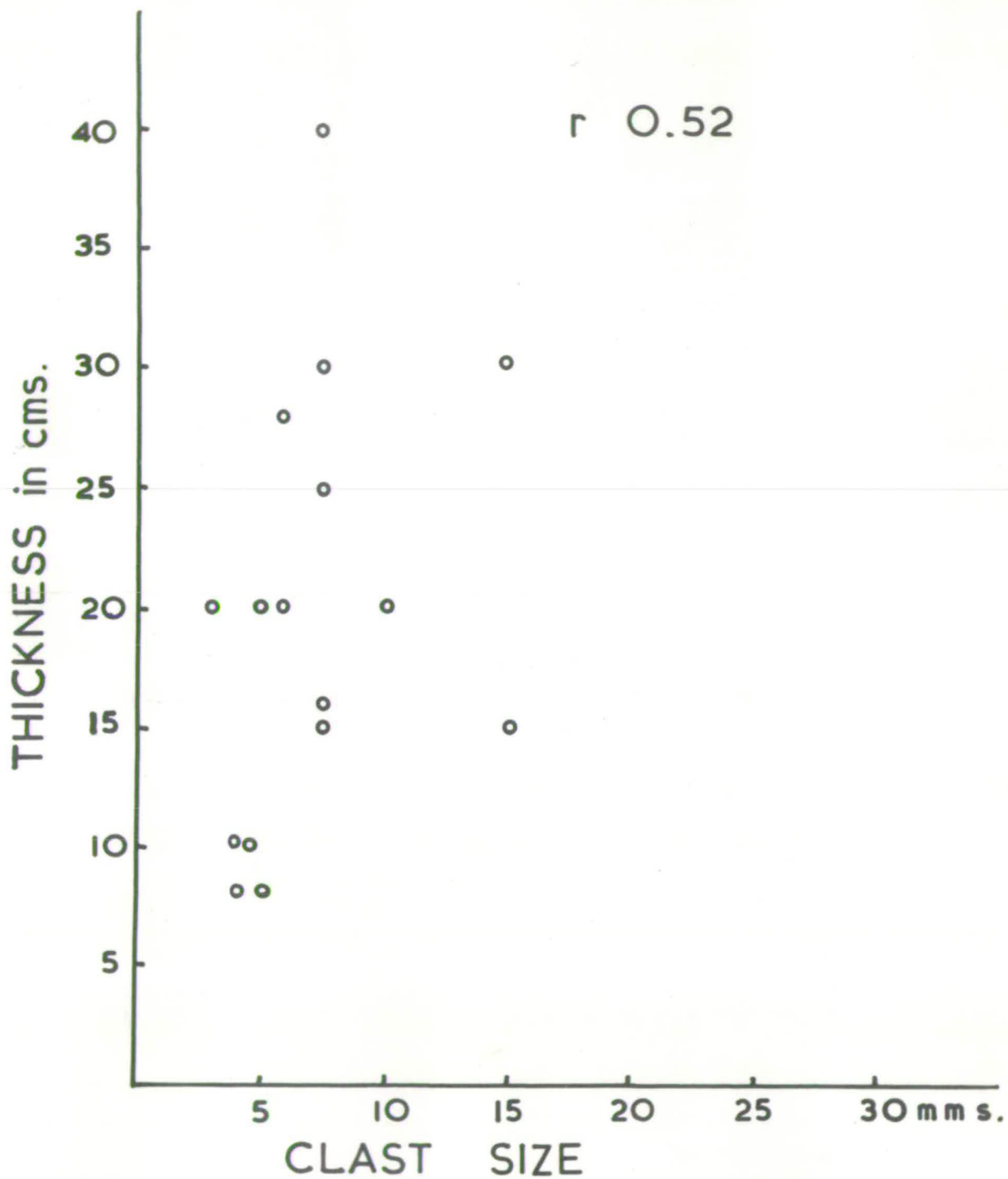


FIG. 15. Maximum clast size plotted against thickness for cross-stratified parts of breccias, breccia facies, Lower Breccia.

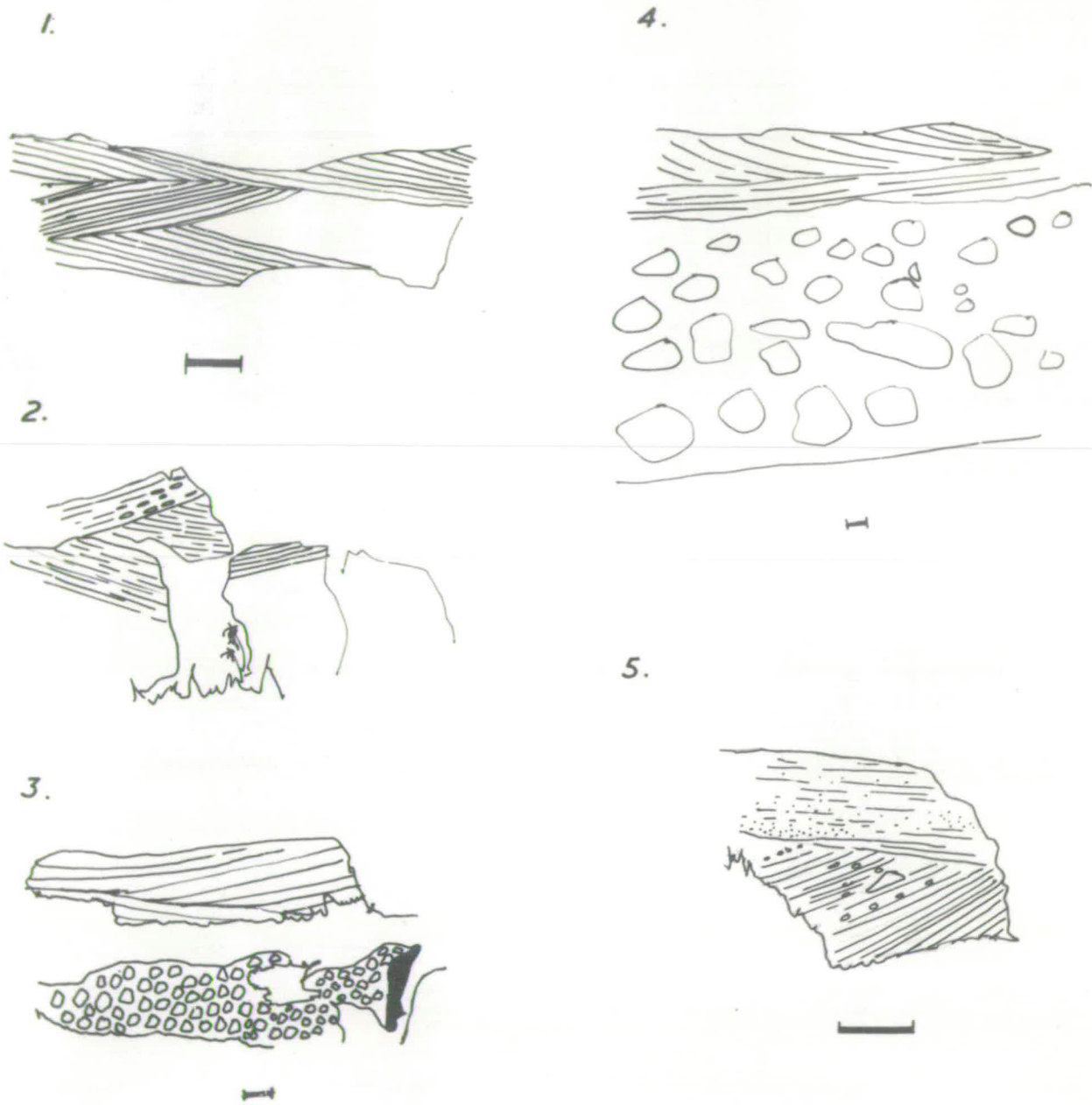


FIG. 16. Types of cross-stratification in the breccias of the breccia facies, Lower Breccia. 1, 2, and 3, are β -type, and 4, and 5, are α -type. Scale bars are 10cm long in each case.

(FIG. 16). The α -types may have resulted from the building-up of a solitary bank, or by the burial of a train of large-scale asymmetrical ripples, as evidenced by a dune-form in one of the breccia tops (Plate 8). β -types are believed to have formed in a similar manner (Allen 1963) but with the solitary bank or ripple train advancing erosively.

Palaeocurrent directions obtained from the cross-stratification at the tops of some breccias are diverse over the whole area, but less so at individual localities, although they may still show a wide spread (FIG. 17). The causes of this variability are thought to be twofold:-

- 1) The regional distribution of the breccias is thought to have been in the form of at least two large fans. Such large-scale features of submarine topography are likely to have had a strong effect on the regional current system. The number of measurements is too small and too scattered to show systematic variations on a regional scale.
- 2) Because of the coarse, lensoid, nature of the breccias, local variations in submarine topography must have been considerable. This would have caused formation of cross-stratification in different orientations according to local conditions of slope in relation to the prevailing currents. For these reasons the palaeocurrent directions indicated by cross-stratification are considered to be consistent with the environment which is envisaged for the deposition of the breccias.

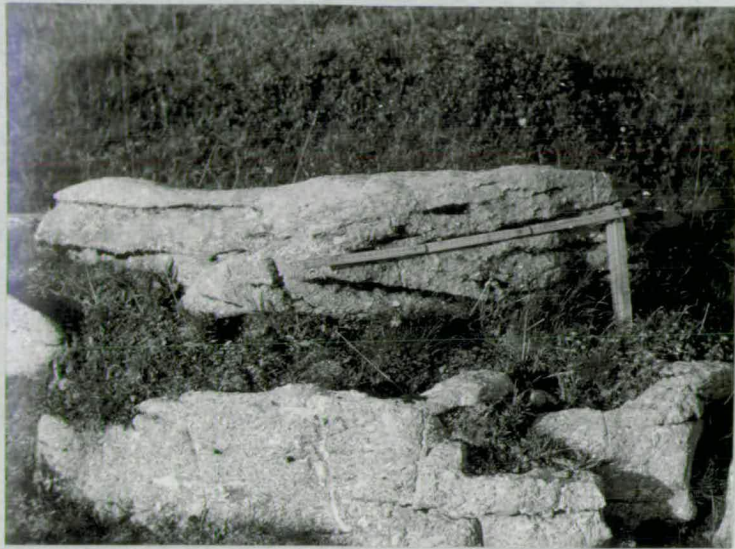


Plate 7. Cross-stratification at top of breccia. Breccia facies, Lower Breccia, Praz de Lys.



Plate 8. Dune form at top of breccia bed. Breccia facies, Lower Breccia, Praz de Lys.

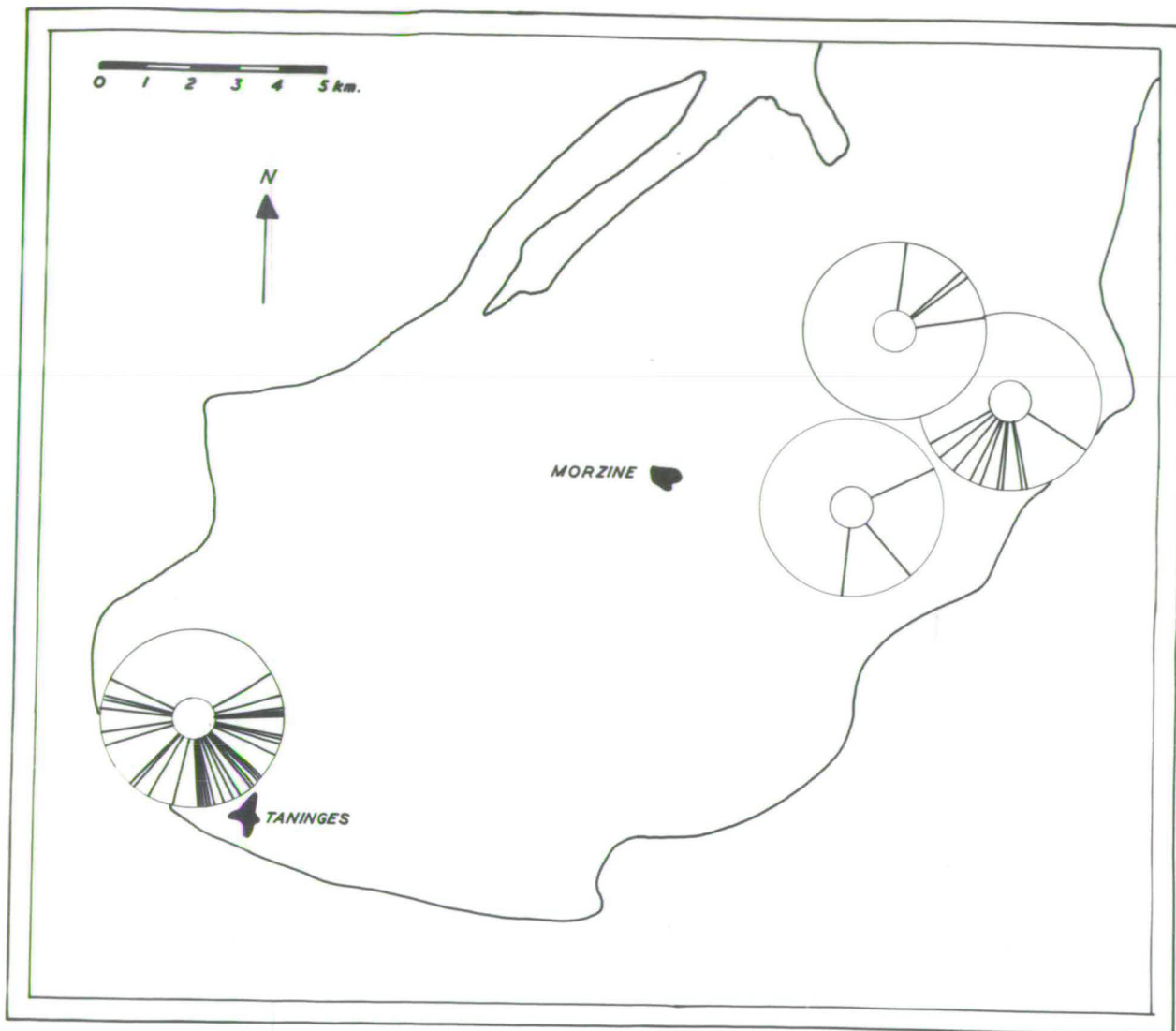


FIG. 17. Palaeocurrent directions deduced from dip of cross-stratification planes, breccia facies, Lower Breccia.

4. Stratification within the breccia beds.

In contrast to the main parts of the breccia beds, the uppermost part of a breccia may be well-bedded or show good parallel or cross-stratification. Stratification is nearly always restricted to the upper part of a breccia bed.

From studies of some breccias in the Praz de Lys area, the following facts emerge:-

- 1) The clast size in the 'structured' part of a breccia is independent of the clast size in the massive part of a breccia (FIG. 18).
- 2) There is a positive correlation between maximum clast size and thickness for the cross-stratified sets at the tops of breccias (FIG. 15). However, if the parallel stratified parts and cosets of cross-strata are also considered (FIG. 19), the correlation with maximum clast size is negative and insignificant, even at the 20% level. This is a result of the fairly constant thickness of the parallel stratified parts of the breccia regardless of the clast size.
- 3) The range in thickness values for the 'structured' parts of the breccias tends to increase as the thickness values of the massive parts increase (FIG. 20).

The conclusions are:-

- 1) The structures have formed in material below a certain clast size (mostly below 10 mm), indicating that the local currents were incapable of moving clasts coarser than this.

CLAST SIZE IN 'STRUCTURED' PART.

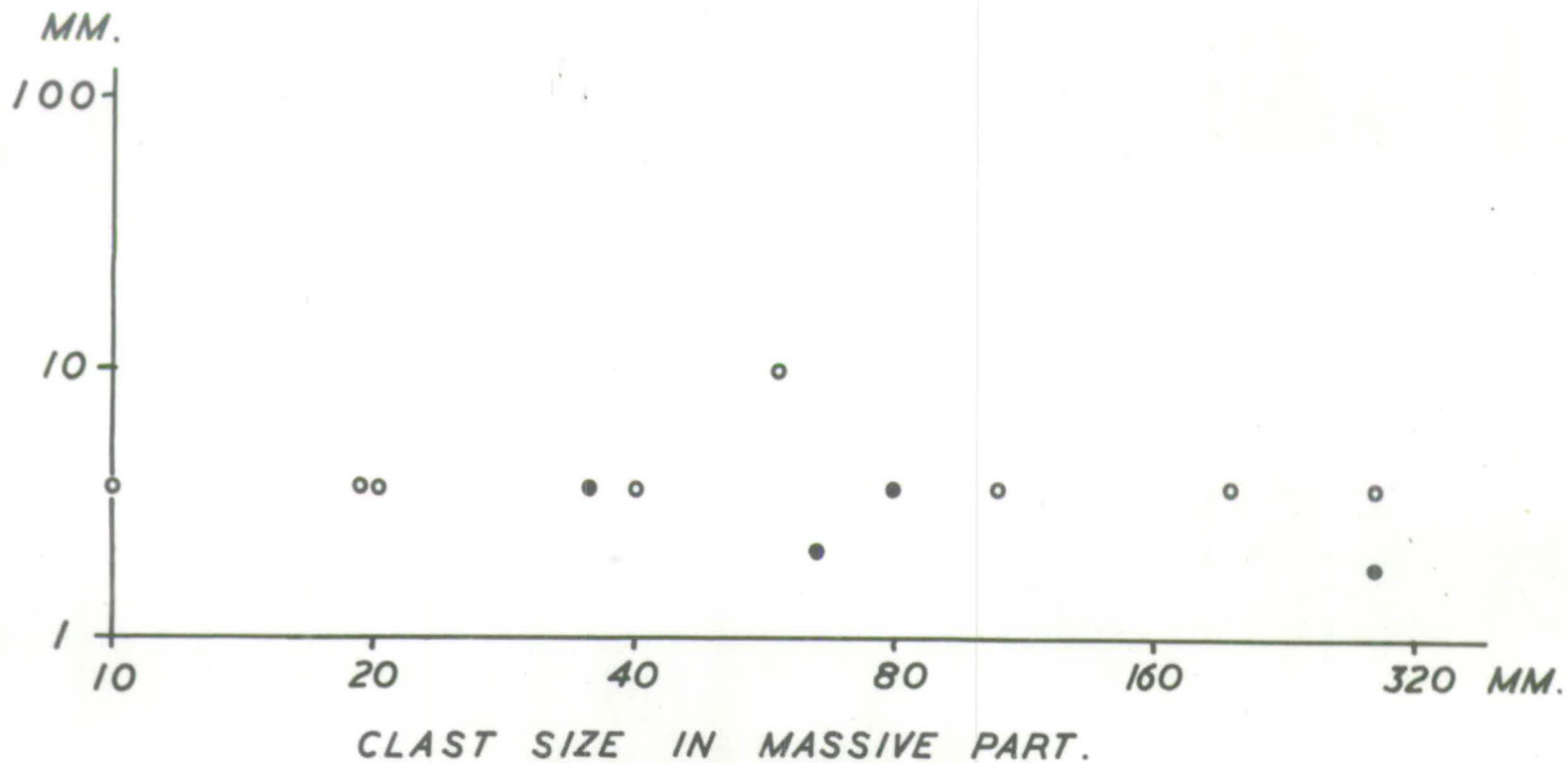


FIG. 18. Clast size in 'structured' parts plotted against that in massive parts of breccias in the breccia facies, Lower Breccia.

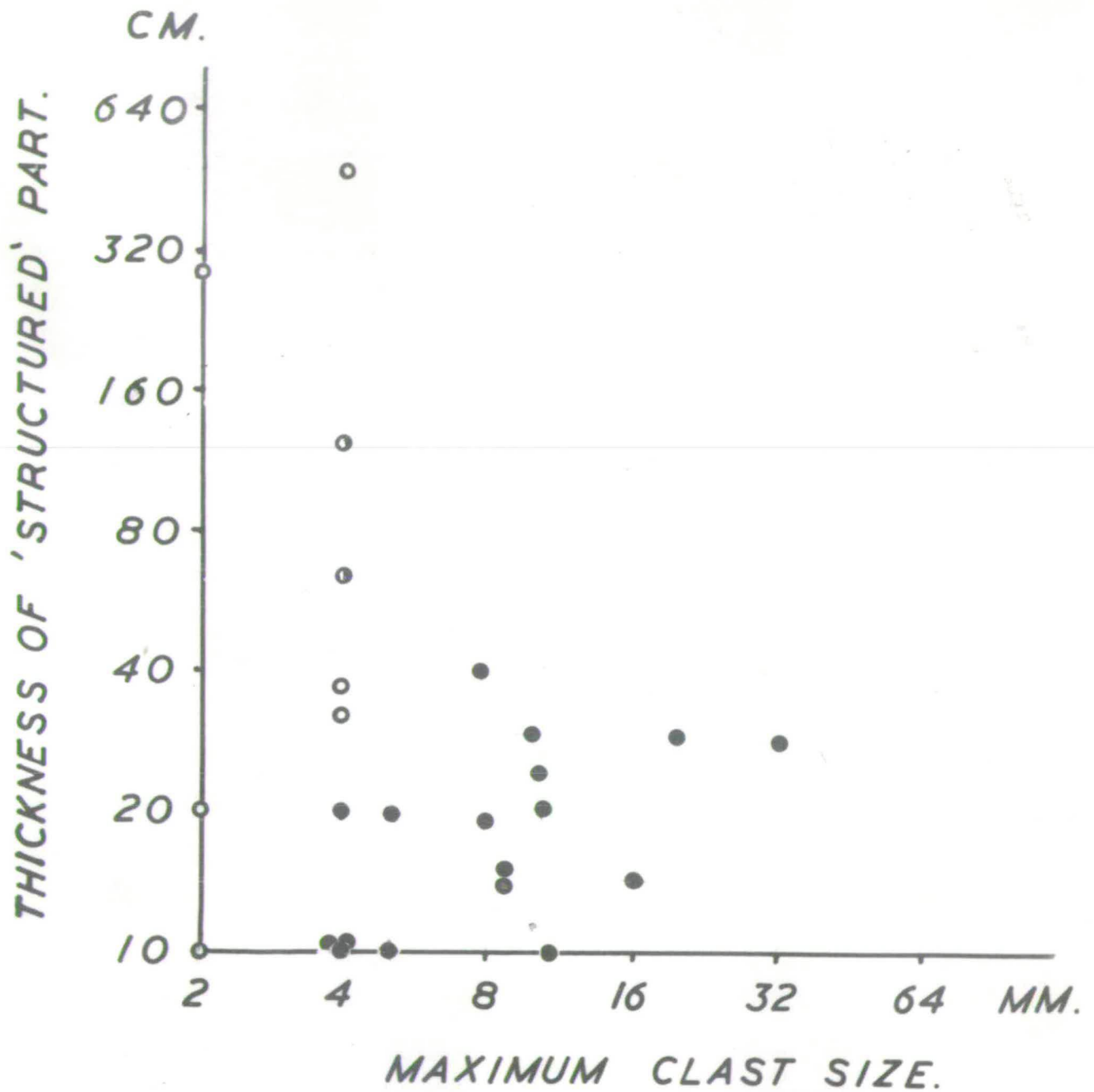


FIG. 19. Thickness plotted against clast size for 'structured' parts in breccias, breccia facies, Lower Breccia. ● - single sets of cross-strata; ● - cosets of cross-strata; ○ - parallel stratification.

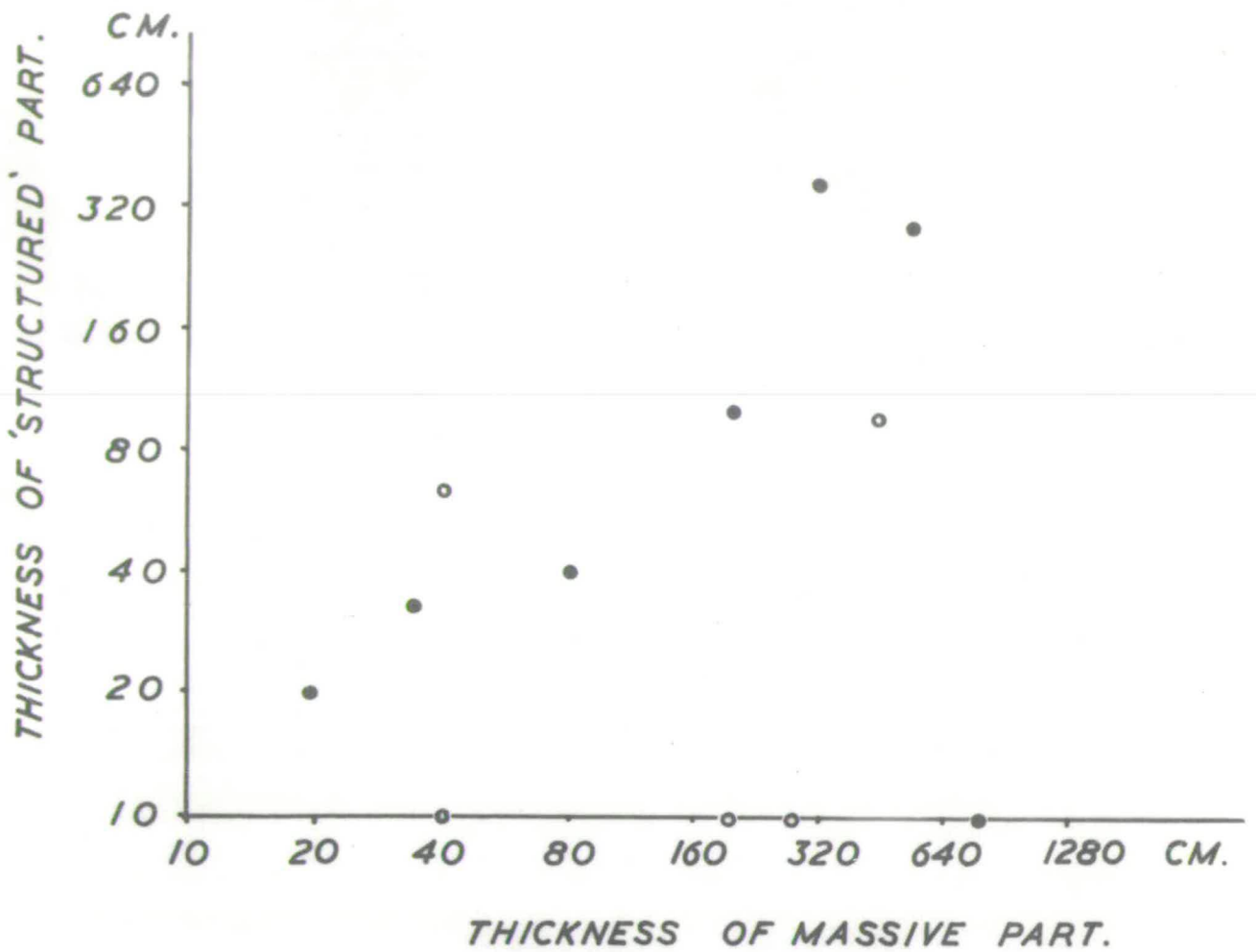


FIG. 20. Thickness of 'structured' parts plotted against thickness for massive parts in breccias, breccia facies, Lower Breccia.

- 2) Either the currents were intermittent or of variable power, or, the amount of available sediment of suitable grain size varied with time. The latter seems to be favoured, as evidenced by (3) below.
- 3) The largest quantities of fine material were introduced along with the thickest beds. Since large quantities of fine material (i.e. thick 'structured' parts) do not occur along with thin massive parts it appears that introduction of fine material depended on the simultaneous introduction of coarse material. Any fine material, which was presumably introduced by the same process as the coarse material must have been reworked by currents which were too weak to affect the cobbles and boulders.

8. The sequence of internal structures in the breccias.

The structures within a single breccia bed generally follow one of three patterns:-

- 1) Single bed with unbroken, but usually slight, clast size grading from bottom to top.
- 2) Bed with massive, coarse lower portion, and an upper finer, horizontally and/or cross-stratified portion. There is usually, but not always, a marked clast-size break between the two.
- 3) Bed composed entirely of a massive ungraded breccia with no fine portion. Such beds may have originally been beds of type (2) from which the fine top was removed by erosion.

In thirty-nine breccia beds which were examined, type (2) was the most common, and type (3) the least common (FIG. 21).

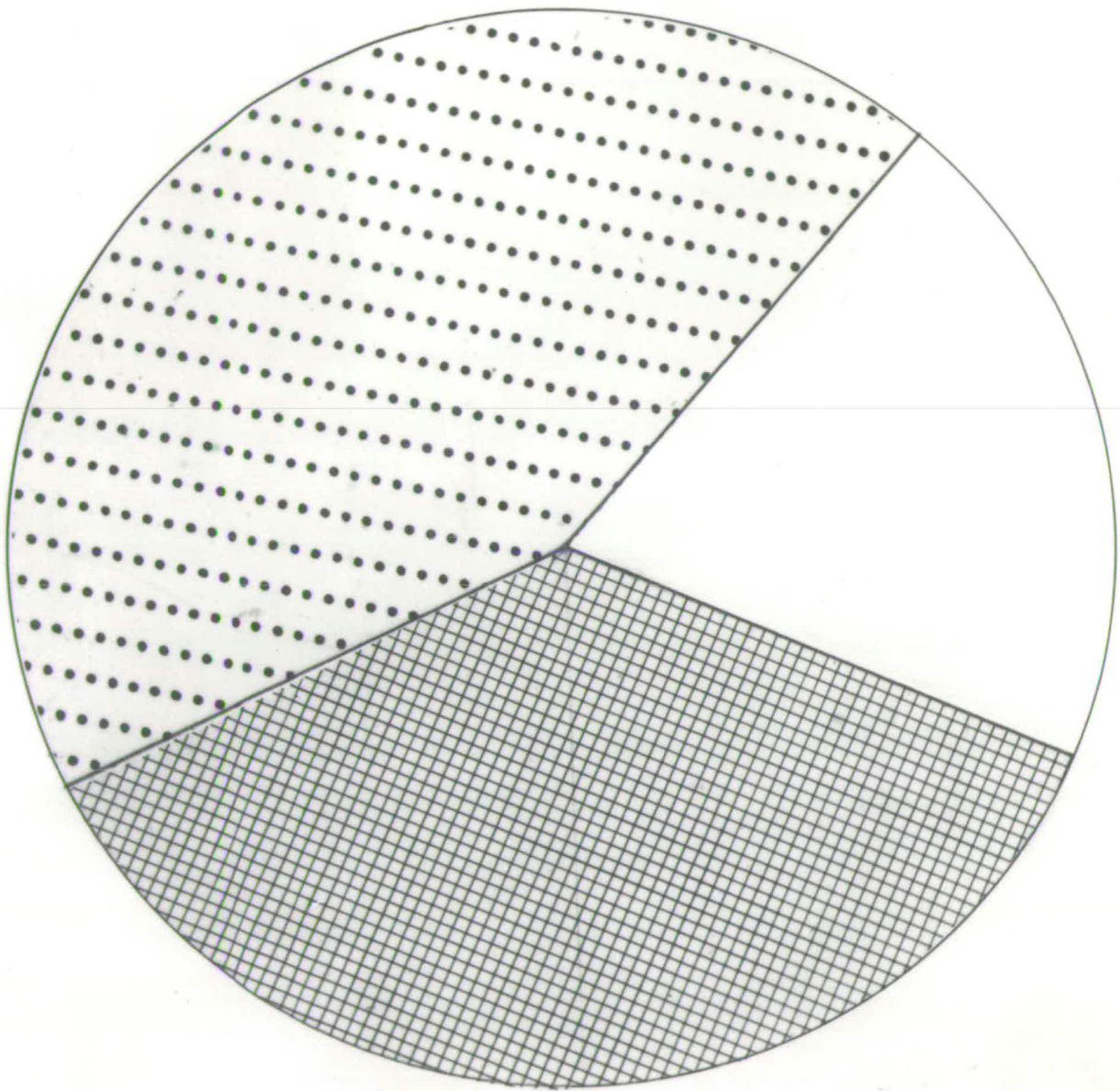


FIG. 21. Proportions of three types of sequence of internal structures in breccias, breccia facies, Lower Breccia. Cross-hatched - graded; dotted - fine top; no ornament - no change.

Most of the breccias fine upwards and the fining is associated with the appearance of either horizontal or cross-stratification. The massive nature of the lower part of a bed is probably the result of currents being too weak to move such coarse clasts.

The common sequence suggests that each depositional event involved introduction of very coarse, often thick breccia. This was followed by current reworking of small pebbles and finer material to produce the stratified tops of many beds. The fairly constant clast-size above which stratification does not occur, suggests an upper limit, and therefore limited variation in current strength.

9. Discussion of a possible bottom current origin.

The cross-stratification in the breccias could have been produced only by bed traction due to bottom currents. It remains to decide if the material forming the breccias was introduced by these currents. The alternative is that introduction to the depositional area was by some other means (possibly gravity controlled) then currents reworked the gravel and finer material.

Considering the first possibility i.e. introduction and deposition by normal currents, the largest boulders could only have been moved into the depositional area by rolling. Apart from this, each breccia bed must have been transported and deposited clast by clast. This means a fluctuation in current strength to allow deposition alternately of sand and cobbles. These changes in current power must involve a gradual waning in

strength of a current capable of transporting cobbles and boulders to a current which would form cross-lamination in granule and sand material, then a sudden increase in current power to supply the next breccia bed. Only in this way, can the gradation from coarse to fine and the change from massive to structured parts in many of the breccias be satisfactorily explained if a bottom current origin is invoked. Field studies show that rarely in the deposition of the breccias was only sand supplied. Also, when coarser material was being supplied, presumably by stronger currents, all finer material would by-pass the area to be deposited as a current-laid deposit elsewhere. The only beds which could possibly be lateral equivalents of these breccias are poorly sorted graded beds with no evidence of bottom current action.

The unique case of a sand lens within, and near the base of, a breccia bed (Plate 9) can only be explained by bottom current deposition. Since such lenses are not common, however, it must be assumed that in general a breccia bed was deposited too rapidly to allow their formation. Thus the normal situation where fine, sometimes sandy, more often gravelly, material is found at the tops of individual breccia beds, can be explained as deposition and/or reworking of fine sediment in the lull or break in coarse deposition between main breccia episodes. Thin, laminated, sandy lenses have been described from the Kilranny Conglomerate, U. Ord. at Girvan, Scotland (Hubert 1966). However, in the Kilranny Conglomerate the sand lenses occur at several levels through the conglomerates, whereas in the breccias



Plate 9. Sand lenses at base of breccia bed. Breccia facies, Lower Breccia, Les lindarets.

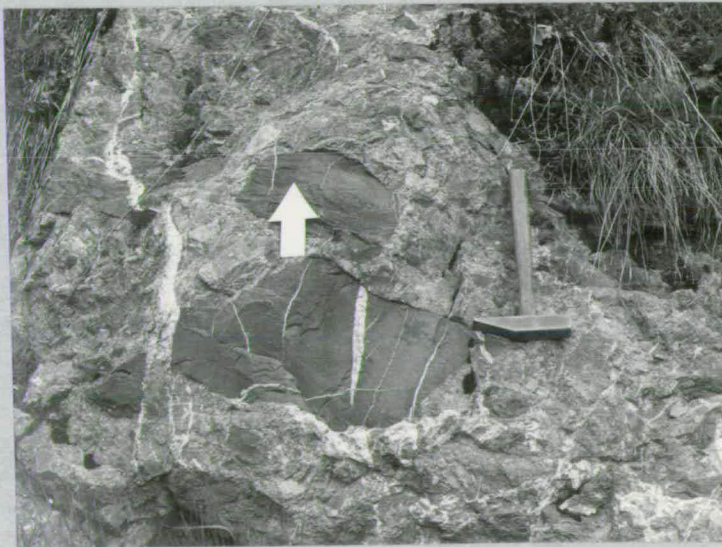


Plate 10. Breccia analysed for imbrication of lamination planes in the large calc-siltstone clasts (arrowed). Breccia facies, Lower Breccia, near Rond.

the finer material is located at the tops of individual sedimentation units except in the case described above. Comparison of the Lower Breccia breccias with other coarse deposits which do not have associated turbidites, Table 1, shows the principal differences are that the breccias have smooth, regular bedding-planes, cross and horizontal stratification, and grading. None of the explanations offered for these other deposits is adequate for the breccias.

If bottom currents introduced even the horizontal or cross stratified gravel; then there is no reason why considerable thicknesses of stratified gravel ^{should not have been} ~~were not~~ built up without associated breccia beds. To avoid postulating a rather strict control of sediment supply, it must be assumed that the currents reworked gravel which was introduced by some other means.

In summary, deposition and transport of the breccias by normal currents alone is not considered likely in view of the wide, but systematic, variations in current power which this would require. Although bottom currents have operated in the area (cross-stratification and laminated sands) there is no clear evidence of the deposition of the coarsest sediment by current action. Thus, any alternative theory erected to account for the transport and deposition of the breccias must explain the pebble lineation and imbrication which have been found in the coarse parts of the breccias.

10. Clast lineation and imbrication.

The basal surfaces of breccias are seldom exposed. However, in one case at Praz de Lys it was possible to measure

TABLE I.

Comparison of breccias of the lower part of the Breche Inferieure with coarse non-turbidite facies sediments from other areas.

	<u>1.</u>	<u>2.</u>	<u>3.</u>	<u>4.</u>	<u>5.</u>	<u>6.</u>
Thick beds.	X	X	X	X		X
Coarse clasts.	X	X	X	X		X
X-bedded throughout.			X	X		
X-bedded at top.						X
Parallel lamination						X
Grading.		X				X
Mud matrix		X				
Clast lineation.						X
Imbrication.	X					X
Interlaminated ssts.	X	X				x ^{1.}
Erosional sole features.		X		X		
Smooth bedding planes.						X
Irregular bedding planes	X	X				

Sources of data.

column no. 1.	Hubert 1966.	Kilranny conglomerate, Girvan.
2.	Bluck 1967.	Alluvial fan, mudflow. River Clyde area. O.R.S.
3.	Bluck 1967.	Alluvial fan, stream. River Clyde area. O.R.S.
4.	Bluck 1967.	Braided stream. River Clyde area. O.R.S.
5.	Bluck 1967.	River channel. River Clyde area. O.R.S.
6.	Present study.	Breccias in the lower part of the Breche Inferieure Formation.

NOTES.

1. One case of interlaminated sand grade material, at Les Lindarets. See text and plate.

the orientation of the major axes of elongate clasts. A marked preferred orientation was revealed (FIG. 22) after unrolling about the local strike. The breccia bed in which the measurements were made was about 300-400 cm thick, ungraded, with a maximum clast size of about 600 m (boulder) and an average clast size of around 50 mm (pebble). The area of the lower bedding plane was about 9 sq. metres, in which about forty of the clasts were elongate - this number was estimated to be less than 1% of all the clasts in the measurement area.

The strong preferred orientation reflects the most stable position of the elongate clasts after their deposition. It also indicates that conditions of deposition were favourable for rotation of clasts into this position either during or after deposition. Normally, the preferred orientation of grains in flowing water is formed by rotation of the grains after their deposition (Schwarzacher 1951; Rusnak 1957). So production of a preferred orientation depends on slow deposition of the whole deposit so that grains can attain their most stable position before burial. The only factor likely to inhibit development of a good preferred orientation, given suitable conditions of flow, and deposition rate, is the influence of adjacent grains. If an elongate clast is deposited between other clasts, rotation to a position stable in the prevailing flow, may not be possible.

The only other way in which a preferred orientation may form is by the development of a fabric during transport, then deposition without destruction of the fabric, may take place, as

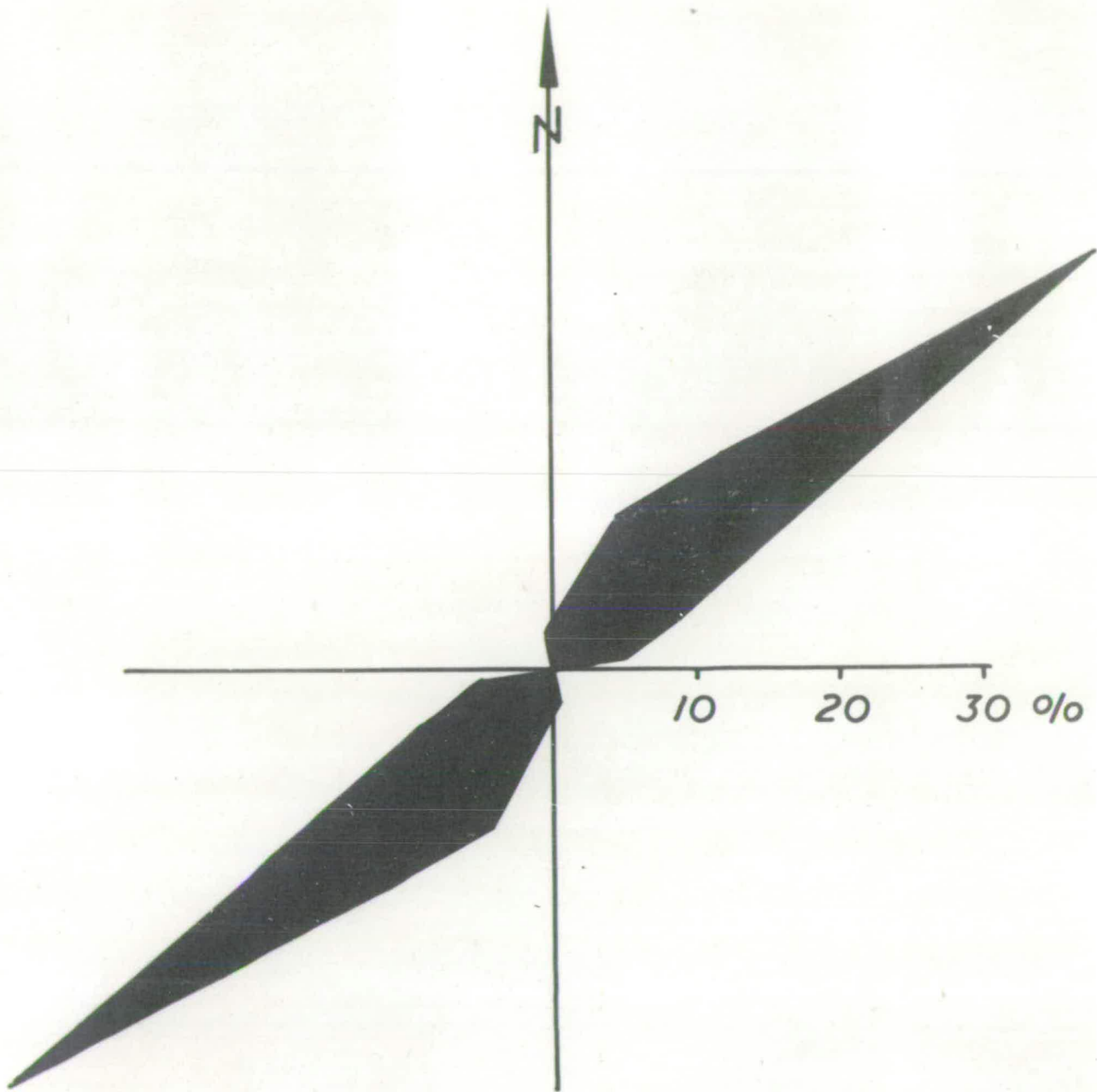


FIG. 22. Pebble lineation in breccia, breccia facies, Lower Breccia, Praz de Lys.

"Elongation" of clasts is $\geq 1.7/1$

in mud flows (Lindsay 1968). There is no question of mud flow transport here, so the following alternatives remain:-

1. Deposition gradually by normal bottom currents, with each elongate clast being rotated to its most stable position after deposition.
2. Attainment of elongate clast fabric during transport, then deposition without destruction of the fabric.

The very high degree of preferred orientation has been achieved in spite of the possibility of destruction by grain interaction. The coarseness of the breccias makes clast by clast deposition from normal currents unlikely. It is therefore concluded that the high degree of preferred orientation at the base of the breccia has been imposed by a grain flow type of transport, with little deviation from this orientation during or after deposition, probably as a result of fairly rapid deposition.

Clasts do not weather out of the breccia outcrops so it is impossible to measure the dips of ab planes of discoidal clasts. At one locality, near Rond, the dips of lamination planes within large calc-siltstone clasts (Plate 10) were measured. It is assumed that the clasts are tabular as a result of control of splitting by the lamination planes. Although the sample is small, plotting the poles to these planes shows a pronounced imbrication with north-west dip (FIG. 23). If this imbrication is assumed to dip towards source, as is generally the case, it agrees with the palaeogeographic reconstruction arrived at by other means. The large size of these clasts makes it very unlikely that they were current deposited.

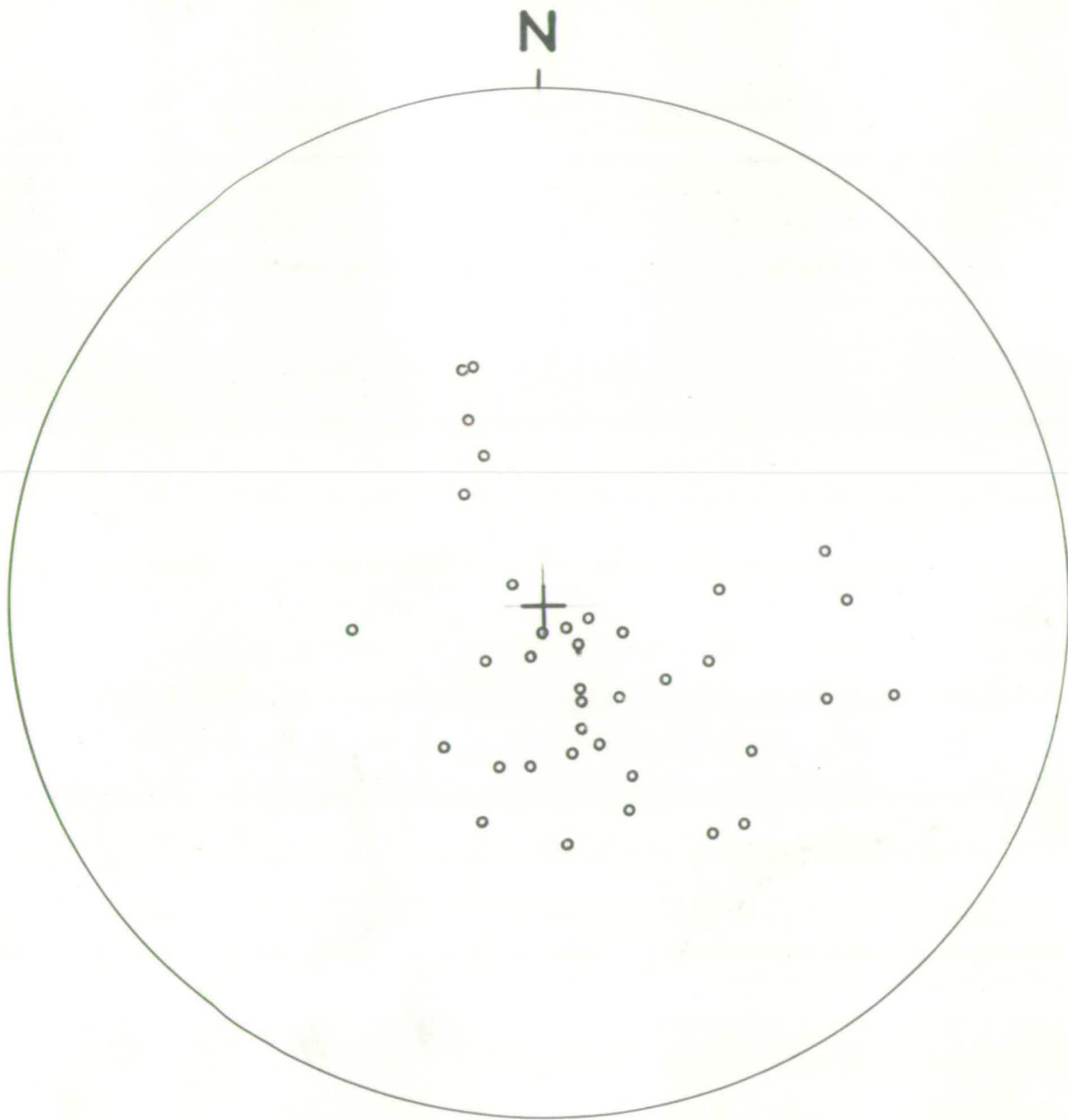


FIG. 23. Imbrication in breccia, breccia facies, Lower Breccia, Rond.
Diagram shows poles to lamination planes in calcareous
shale clasts.

11. Sand and mud in the breccias.

Sand is a minor component in the coarse parts of all breccias, but increases in proportion as the size of the largest phenoclast decreases. Mud is absent from the breccias, the finest material generally being fine/medium sand (Plate 11). In a typical pebble breccia (Plate 12) most of the intergranular material is granule grade with some sand. Field studies of the basal parts of some of the coarse breccias show that the cobbles and boulders have almost no intergranular sand - the finest material is generally granule size. In the breccia which was analysed for grading, histograms of clast size distribution at levels through the bed show no sand except at the very top (FIG. 24). It is considered unlikely that such coarse breccias were deposited from bottom currents, although bottom currents may have operated in the depositional area (p. 20). The presumed indigenous currents which formed the cross-stratification at the tops of some beds would have been powerful enough to remove any mud from the tops of breccia beds. However, there is no mud in the lower massive parts of the breccias, so that either,

- 1) the accumulation of a complete breccia bed must have been gradual to allow the removal of any mud which would otherwise have been trapped between clasts.

or

- 2) There was almost no mud supplied with the material in the breccias, any mud having been removed at initial site of accumulation of the breccia material.



Plate 11. The finest material found in the breccias of the breccia facies. Lower Breccia, near Les Lindarets. Scale in cm.

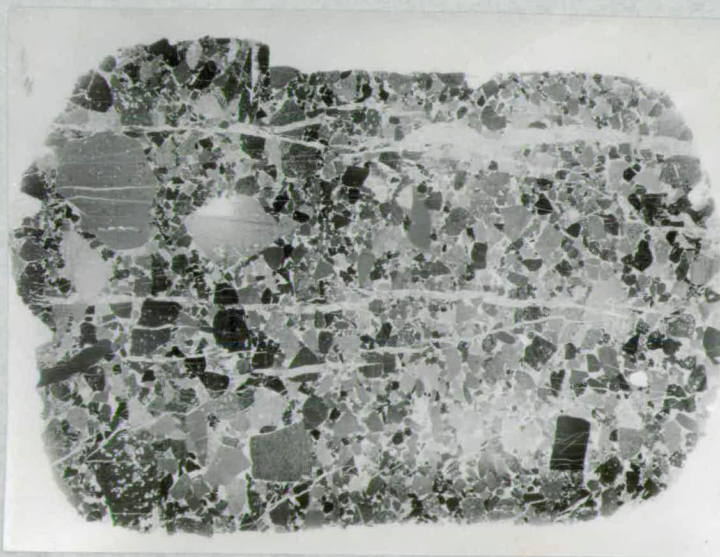


Plate 12. Typical pebble breccia showing sand/granule grade intergranular material. Breccia facies, Lower Breccia. Length of specimen - 9 cm.

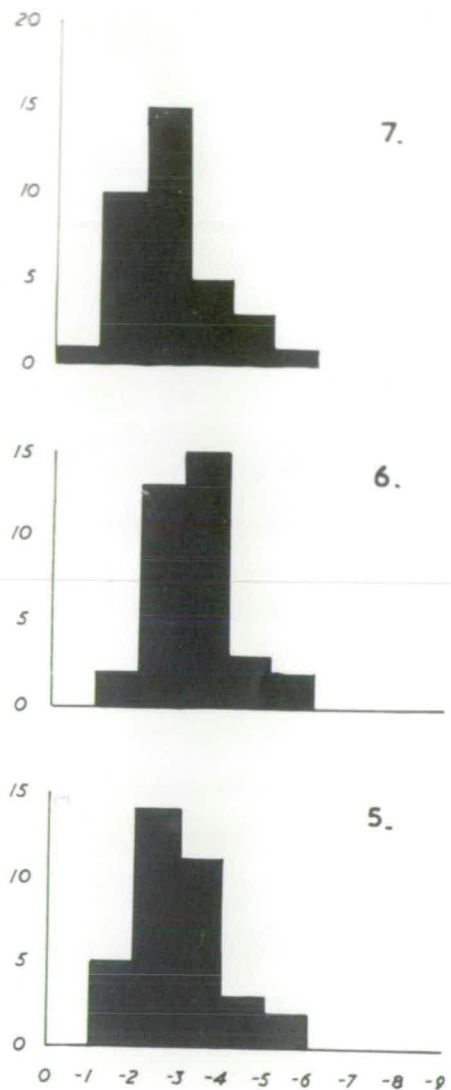
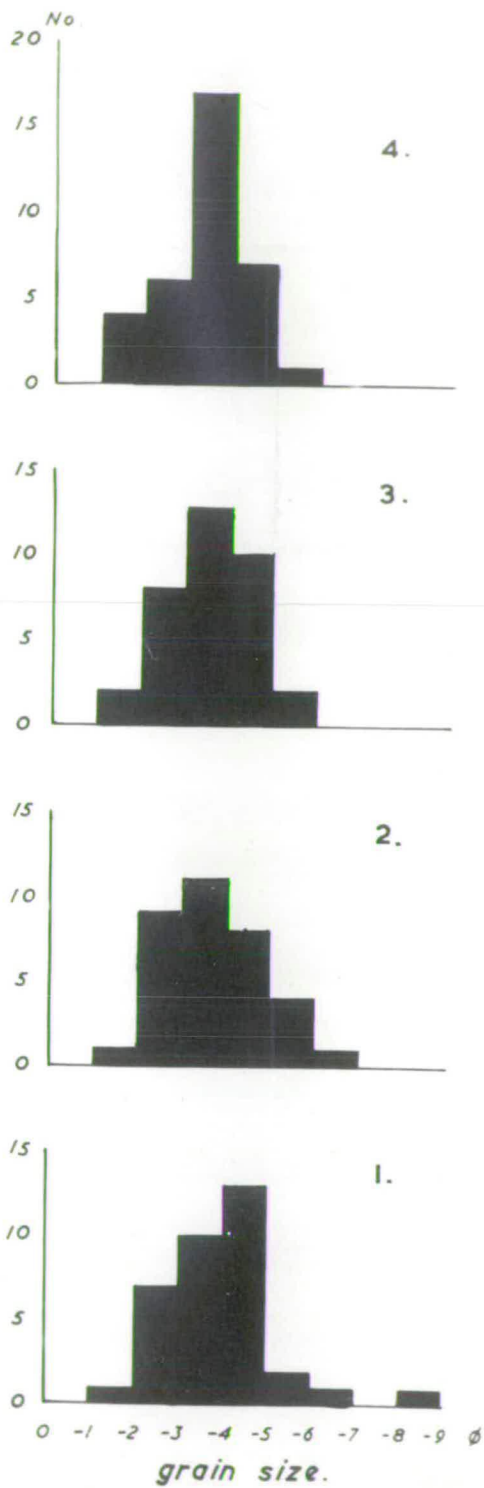


FIG. 24. Clast size analyses from bottom to top (1 - 7) of a graded breccia in the breccia facies, Lower Breccia, Praz de Lys.

The extreme variation in clast size through some of the breccias, and the marked upper limit to the clast sizes which occur in the horizontally - or cross-stratified parts of the breccias suggest that the coarsest material found in the breccias was probably not introduced by bottom currents. The coarse, structureless parts of the beds were probably transported 'en masse', which implies that any mud which was originally present must have been removed at the original site of accumulation.

Any mud, and much of the sand, which was supplied to the basin, was presumably transported in turbidity flows or in colloidal suspension, further into the basin where it was deposited as a sequence of graded beds (now seen along the road from Pont des Gets to Avonnes), or shales with occasional graded beds and breccias (now seen as the Lower Shales).

It seems possible, therefore, that the material which forms the breccias was fairly free of mud at its original site of accumulation, although the poorly rounded nature of the clasts suggests that if the mud was removed by currents, these currents were not normally strong enough to move the gravel.

12. Possibility of origin as submarine slides or flows.

The theory of a submarine slide origin for the breccias (Lugeon 1896; Schroeder 1939; Arbenz 1947; Kuenen and Carozzi 1953; Chessex 1959), may explain the massive coarse parts of the beds. Their features bear comparison with other coarse deposits reported from turbidite sequences. The feature most commonly reported from rocks of supposed slide origin is, however, absent

from the breccias. Kuenen (1953), Dzulynski et al., (1959), and Unrug (1963, 1964) all describe cases of soft sediment deformation, either as slabs of folded sediments or as soft deformed clasts in the supposedly slumped beds. However, the presence of soft sediment deformation implies only that there was partially consolidated sediment in the source area, and the lack of such features is a direct result of provenance of the sediments, or the process of transport has been a type of flow (see p. 30) rather than a slide.

Features of the breccias compared with those features found in 'proximal' turbidites and 'fluxoturbidites' (Table II), show that the breccias have more in common with fluxoturbidites than with proximal turbidites. This is largely because the breccias, and the deposits which fit the description of fluxoturbidites by Dzulynski et al., (1959), are much coarser than the deposits named 'proximal' turbidites by Walker (1967). As Walker (1967) claims, and indeed demonstrates in the descriptions which he quotes, the term 'fluxoturbidite' has not been well defined, and has been used in a vague and confusing manner. I endorse this view and prefer to continue with the term 'breccia', because of its non-genetic significance.

Comments on the numbered notes of Table II are:-

- 1) Some of the breccias are well-graded.
- 2) Beds have irregular thickness on a large scale (sq. kms.) only.
- 3) There are no clear cases of interbedded turbidites.
(However, see next section).
- 4) Cross-stratification and horizontal stratification of

TABLE II.

Comparison of proximal turbidite/fluxoturbidite features
with those of the breccias of the lower part of the Breche
Inferieure.

	Proximal Turbidites	"Fluxo- turbidites"	Lower Breccia
Beds coarse grained.	X	X	X
Beds thick.	X	X	X
Grading poor or absent.	X	X	x ^{1.}
Multiple beds; repeated grading common.	X	X	0
Mudstone partings thin or absent.	X	X	X
Beds irregular in thickness.	X	X	x ^{2.}
Beds parallel sided.	0	0	X
Beds interbedded with turbidites.	X	X	x ^{3.}
Sole marks scarce.	0	X	X
Conglomerates/sandstones clean.	0	X	X
Mud flakes.	X	0	0
Large scale cross stratification present.	0	X	X
Scouring and channeling common.	X	0	0
Sharp tops and bases to beds.	X	X	X
Tops have linguoid ripples.	X	X	0
Indications of soft sediment slumping.	0	X	0
Laminations and ripples scarce as internal structures.	X	X	x ^{4.}

Data from Walker (1967). The reports quoted by Walker (1967) of Stanley (1963), Kuenen (1964), and Rizzini and Passega (1964) are considered to describe proximal turbidites as described by Walker (1967), rather than 'fluxoturbidites' as described by Dzulynski et al., (1959).

X - Feature is present. 0 - Feature is absent. x - Comment qualified in text.

gravel grade material is present, but no small scale horizontal or ripple lamination occurs in sand when it is present.

The relationship of the fine 'structured', and the coarse massive parts of the breccias has been discussed (p. 17). The simplest suggestion for the origin of the coarse parts, or the graded parts, is a flow. The mode of formation of grading in such beds is discussed elsewhere (p. 28). The clast lineation and imbrication which has been found, is considered compatible with a flow origin (p. 21), although there are no other reports in the literature which confirm this.

13. Interbedded Turbidites.

Where breccia development is at a maximum, interbedded graded sand or gravel beds are not found, but towards the top of the breccia sequence some thinner turbidites occur. However, the change to the overlying flysch facies is transitional though rapid, and does not involve much interbedding of the breccias and turbidites. It seems possible that the source area of the breccias supplied little sand, so that while breccia deposition was taking place there was only a small chance of deposition of finer graded beds. Alternatively, any fine graded beds which were deposited, may well have been reworked by the bottom currents, into beds with parallel, or cross-stratification, or, fine-grained turbidites may have by-passed completely the depositional area of the breccias, to be deposited further out in the basin.

14. The significance of grading in the breccias, and the possible mechanism of transport.

Experiments on the formation of graded bedding (Kuenen and Migliorini 1950; Middleton 1967) involved deposition of sediment from a turbulent suspension. The large sizes found in the breccias suggest that transport by suspension did not take place. The importance of autosuspension in the maintenance of turbidity currents is restricted to sediments below a critical size of 50 μ (Bagnold 1962). The maximum diameter for viscous settling of spherical particles in water is around 100 μ (Inman in Shepard 1953). For material coarser than sand, inertial settling takes place, and viscous effects are negligible when water is the fluid phase. If the fluid phase is a mud suspension, the limits of viscous settling are extended. There is, however, no mud in the breccias. The breccias must have been transported as a flow of rock fragments, propelled by the energy gained by virtue of their initial downslope movement. Autosuspension cannot have contributed to the transporting process. This means that deposition would take place as soon as internal friction forces equalled the downslope component of gravitational attraction. Although the dispersive stress as a result of grain collisions (Bagnold 1954, 1968) would tend to delay 'freezing' of the flow, deposition from an inertia flow would be more rapid than from a turbulent suspension. The high concentration of solids in such a flow would also tend to inhibit segregation of clasts according to size, thus preventing good grading. In experiments, the best grading is by deposition from currents of low density (Middleton 1967). It has been shown above (p. 14)

that grading does occur in some of the breccias. Since the possibility of transport in suspension has been considered unlikely, all of the breccias would be high concentration flows.

The alternative explanation for the formation of the grading is that after initiation of the flow, the coarsest clasts present moved faster and towards the front of the flow. The finer material would flow over the first deposited coarse clasts and degree of grading produced would depend on the perfection of this separation process. Such a process has been suggested by Sanders (1965) for the production of normal grading in inertia flow deposits. It seems to me that this process would be unlikely to produce good grading as is found in turbidites because of the inevitable high degree of interference of grain with grain. This may be demonstrated in the seldom-produced 'extreme' grading in the breccias.

Since a process of inertia flow has been suggested for the origin of the breccias it is necessary to comment on the scarce occurrence of inverse grading. One case at least, (see FIG. 10), shows that the largest clasts are some cms above the base of the bed rather than at the base, but this is the exception. In a granular flow where inertial effects predominate, relatively larger grains should tend to drift towards the zone of least shear strain i.e. the free surface of a gravity flow (Bagnold 1954). Schminke (1967) attributed the inverse grading at the bases of lahars to this effect. Scott (1966) has described a similar type of inverse grading from conglomerates in the Cretaceous of Chile. In both of these cases the deposits

were relatively free of mud. In the ungraded breccias there may not have been a sufficient quantity of very large clasts, or enough time to show the effect. In the case of the graded breccias it has already been suggested that the grading resulted from an initial separation of different sizes - in such a case the largest sizes would move to the front of the flow and tend to form a fairly thin layer, in which inverse grading could not form because the coarse clasts no longer constituted an inhomogeneous mixture with finer clasts.

To summarize, it seems likely that the majority of the breccias formed by a process similar to that described by Sanders (1965) and Stauffer (1967) as inertia grain flow.

A short comment on nomenclature may be relevant. Three main types of movement have been recognized in the study of gravity controlled depositional processes (Varnes 1958; Sharpe 1960; Dott 1963). These are:-

- FALLS : Involving simple breaking off and tumbling downwards to position of rest, of large or small fragments, either singly or in quantity e.g. at sea-cliffs. A fall may be the initial movement in a process developing into a slide or flow, but this need not follow.
- SLIDES : Mass movement on a slip surface. Deformation is not continuous but involves finite shear.
- FLOWS : There is no single slip plane. There is considerable internal shear and movement takes place by continuous deformation.

Parallel alignment of clasts, imbrication, and grading all indicate conditions of flow. The flows may have developed from an initial large scale fall, or slip on an unstable slope. It is unlikely that movement was of slide (s.s.) type except perhaps at first instant of movement.

(ii) Flysch facies.

The upper part of the Lower Breccia Formation is a sequence of graded gravel sand-and silt-grade calcilithite beds with some interbedded breccias (Plate 13). It is easily distinguished from the breccia facies in the field. At its upper limit, the appearance of red and green mudstones marks the Upper Shales, and at the lower limit, the increase in number and thickness of massive breccia beds, with disappearance of finer graded interbeds, marks the top of the breccia facies of the Lower Breccia Formation. Both the upper and the lower limits are transitional.

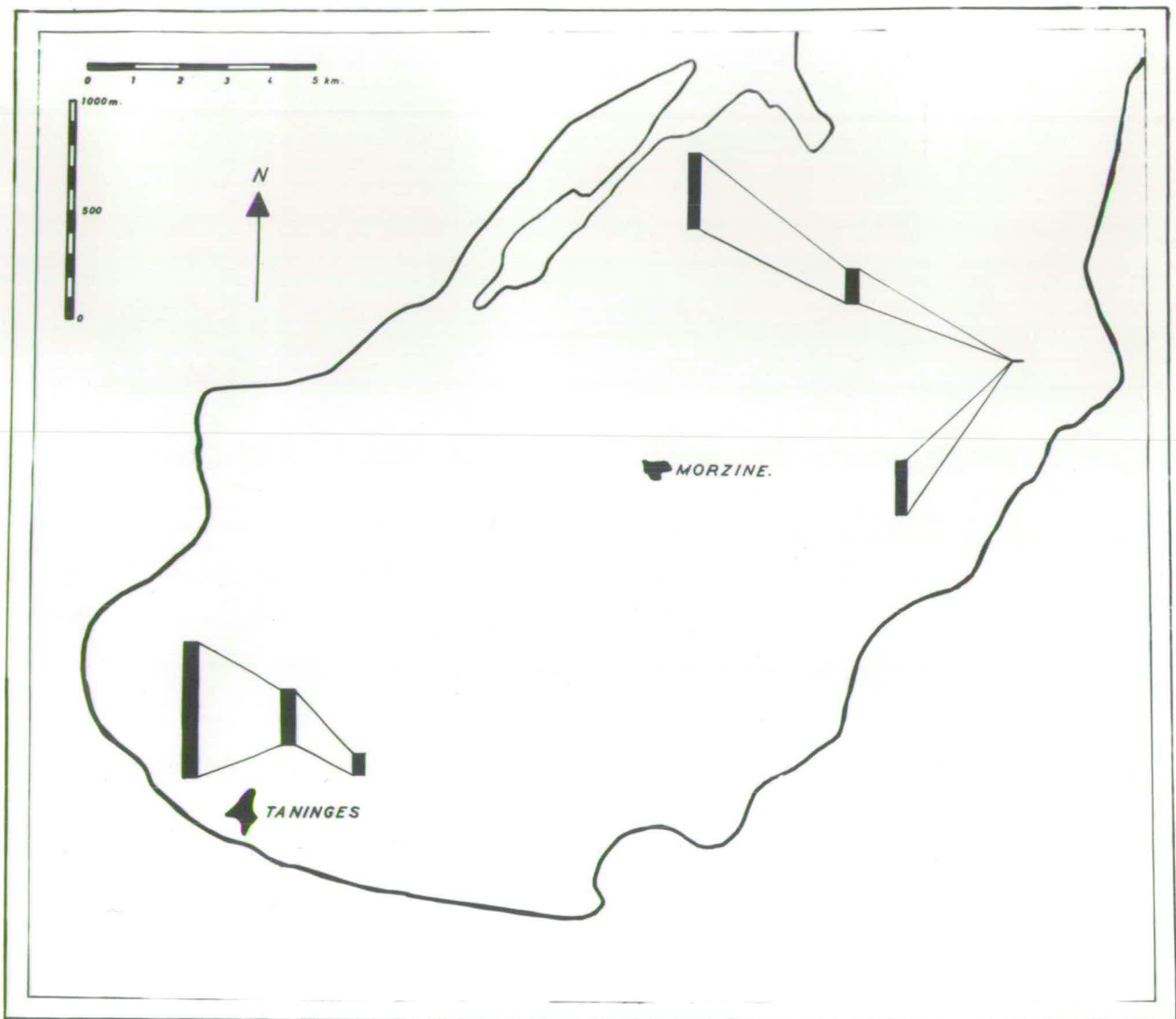
At Pic de Marcelly and Roc de Tavaneuse, the flysch facies is well developed and succeeds the likewise well developed breccia facies. To the south-east side of the nappe (Pont des Gets to Avonnex, La Biolle, Col de Jouplane) the division between the lower and upper parts of the Lower Breccia is not so well marked, and the breccia facies, rather than lying below the flysch facies, has been reduced to breccias interbedded with the flysch facies. The flysch facies shows thinning in an easterly/south-easterly direction in the south-west and north-east parts of the area (FIG. 25). This is accompanied by thinning of the breccia facies except at Col de Chesery where the breccia facies occurs but flysch facies is absent. Thinning of the Lower Breccia Formation is associated with thickening of the Lower Shales (Schroeder 1939). The lateral relationships of the Lower Breccia and Lower Shale Formations may be considered along the south/south-west limit of the nappe near Taninges (FIG. 25).



Plate 13. Flysch facies of Lower Breccia. Praz de Lys.



Plate 14. Lower Breccia sequence between Pont des Gets and Avonnes. Scale at base of section is 1 metre long.



FIG, 25. Areal variations in thickness of the flysch facies, Lower Breccia.

The stratigraphic section from Praz de Lys to the bottom of the south-west face of Pic de Marcelly, in the region of Marcelly, shows about 700 m of breccia facies overlain by about 600 m of flysch facies. There the distinction is easy, the breccia facies has only minor amounts of finer beds and finer sediment, while there are fewer breccias in the flysch facies.

On the other side of the R. Foron the main exposures of the Lower Breccia are along the Route Nationale 202 from Pont des Gets to Avonnoz, and on the Departmental road from Le Mont to La Biolle. These two sections can be considered more or less stratigraphically equivalent. Even if there is a fault along the valley of the Foron, the fact that the base of the Upper Breccia can be traced at approximately the same altitude both on the plateau of La Biolle, and on the plateau of Praz de Lys, suggests there has been minor vertical displacement, if any. Between Pont des Gets and Avonnoz, the Lower Breccia is represented by a series of breccias, graded calcilithites, and shales (Plate 14). Breccias seldom reach the massive proportions of those found in the breccia facies of the Lower Breccia at Pic de Marcelly, and clast sizes are generally pebble/granule grade and finer. Finally, in the region of sur les Chables, the Lower Shales outcrop (Plate 15). Calcareous shales make up about 80% of the section but the interbedded calcilithites are sand and granule grade, with sole markings, and generally around 10 cm thick. Apart from the higher proportion of pelite, the lithologies are similar to the calcilithite/pelite units of the Lower Breccia



Plate 15. The Lower Shales at sur les Chables.



Plate 16. Graded breccia bed in flysch facies. Lower Breccia. Roc de Tavaneuse.

flysch facies. A further similarity is that the particular section shown also has cobble breccias (clasts up to 700 mm) up to 100 cm thick. Thus a facies similar in type to the flysch facies of the Lower Breccia can be traced in the Lower Shales, through a typical Lower Breccia flysch facies, to a breccia facies. Although lack of fossil evidence prohibited proof of contemporaneity, it is notable that in the region studied, the Lower Breccia and the Lower Shales differ in degree rather than type, and field evidence of thickness variations and lithologies suggest a possible lateral transition.

Unfortunately, similar variations cannot be traced in the north-west part of the nappe because the Lower Shales are not present, or they are covered - since they are usually the lowermost formation present in the nappe they are often 'bottomed' by the sole thrust of the nappe, resulting in a decrease in thickness.

Lithologies in the flysch facies.

For convenience of description and ease of recognition in the field, the flysch facies is divided into three lithological types which overlap to a certain degree. The types are as follows:-

1. Breccias. Beds up to 500 cm thick with more than 50% gravel and often with sandy tops (Plate 16).
2. Sand - silt grade calcilithites are transitional with the breccias depending on proportion of gravel. They are generally much thinner than the breccias, however, and are commonly graded and show internal structures similar to those found in turbidites. They have an arbitrary lower thickness limit of 5 cm.
3. Sand - silt grade calcilithite beds below 5 cm in thickness, which alternate with calcareous shales, form the calcilithite-pelite lithology. The pelitic fraction predominates in this type.

Within the flysch facies these three types alternate. The distinctions are made on the basis of both grain size and bed thickness, composition varies little.

1. Breccias.

There are two types of breccias - normal and chaotic. The normal type is by far the more common.

a) Normal type of breccia.

These are found throughout the flysch facies and may constitute up to 45% of the facies by thickness in different local successions. They are texturally and lithologically similar to the breccias of the breccia facies, but comparison of the thickness - frequency distributions (FIG. 26, FIG. 5), shows that they do not attain the maximum thicknesses of the breccias in the lower part of the formation. Clast size is variable but seldom greater than about 100 mm (-6.5 ϕ), (FIG.27). They have sub-angular to sub-rounded clasts of pebble/cobble size, sometimes grading up into sand (Plate 16). In the lower, more massive parts of the beds, there is no mud matrix. The clasts form a closed framework, and there may be some interstitial sand, but not a sand matrix. They differ from the breccias of the breccia facies by always having an associated sandy portion, and in not having cross-stratification in the pebble-granule parts of the bed. The sandy part of a bed may be very thin; it may have cross- or parallel-lamination, and may be overlain by a pelitic portion. These breccias persist laterally over the area of at least the largest outcrops (about 400-500 m).

Structures in the normal type.

(1) External structures.

Breccia soles are seldom exposed but loose blocks

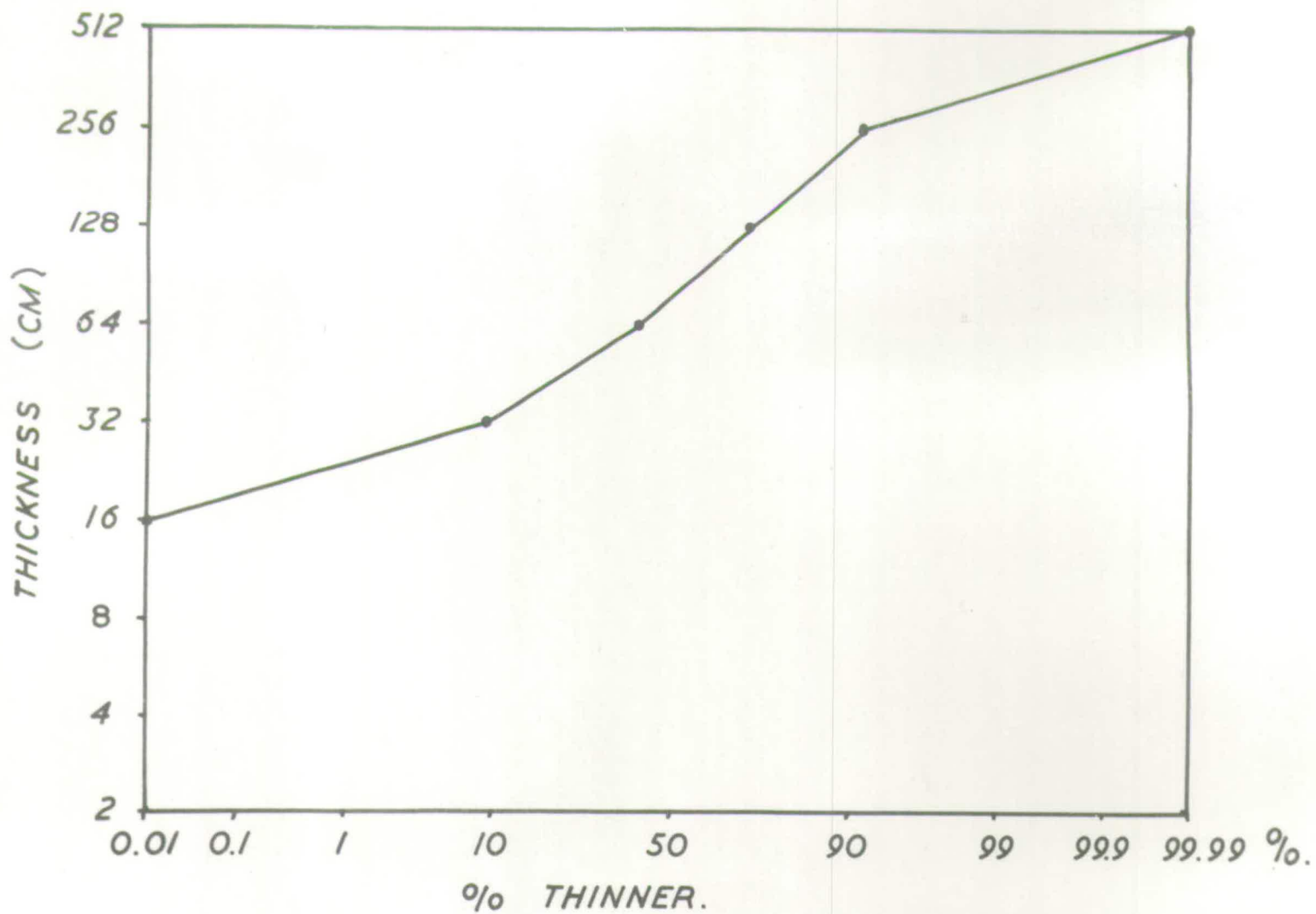


FIG. 26. Cumulative frequency/bed thickness curve for breccias in the flysch facies, Lower Breccia.

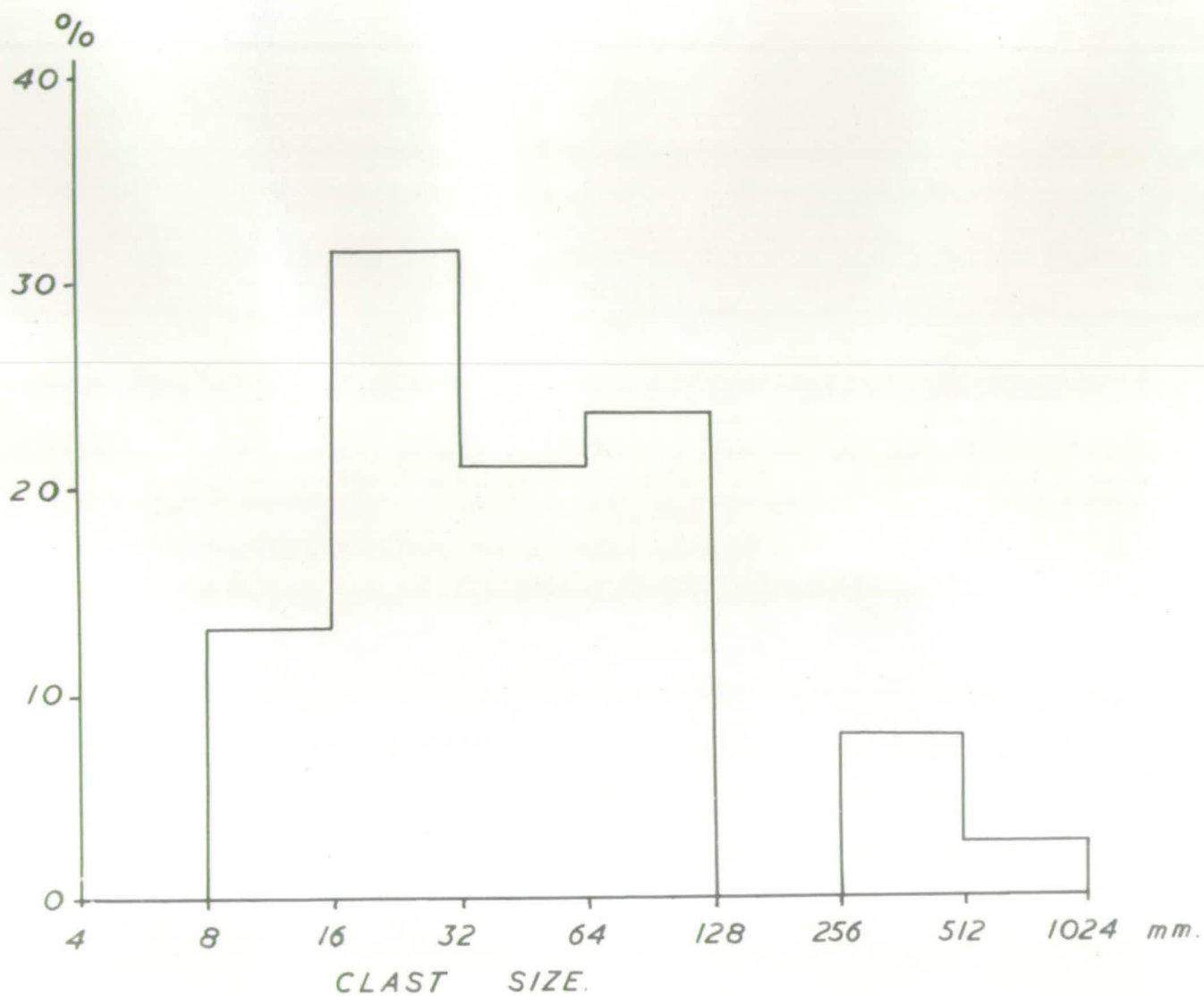


FIG. 27. Maximum clast size in 37 breccias, flysch facies, Lower Breccia.

testify to the presence of large flutes on breccia bases (Plate 17). In spite of intensive searches, no flute markings were found in place on these breccias. This suggests a real, rather than an apparent, lack. There are a few possible reasons for this. The bottom sediment may have had unsuitable properties of cohesion at a time when flutes were likely to form. The bottom material below most of the breccias is generally silt or silty pelite, less commonly it is sandy silt, and it is very seldom clayey pelite. Either lack of cohesion preventing formation of flutes, or so much cohesion that initiation of flutes was not possible, may have been important. With lack of cohesion a turbulent eddy may start to form a flute, but the sediment adjacent to the eroded hollow would cave into the hollow, or the sediment may be able to flow so easily that significant erosion would not be possible. With strong cohesion of bottom sediment eddies may not be strong enough to erode a flute. It has been shown experimentally that cohesion of a clayey sediment is attained more rapidly if silt content is low (Postma 1962). The uppermost parts of most of the beds in the flysch facies are silty rather than clayey. However, the rocks do not give any clue as to the state of their cohesion at the time of deposition of the overlying bed, unless of course erosion features can be seen. Lack of erosion features is purely negative evidence - it may have been controlled by factors other than the cohesion of the bottom sediment.



Plate 17. Large flute on base of breccia bed (loose block). Flysch facies, Lower Breccia, Praz de Lys.



Plate 18. Load deformation at base of breccia bed. Flysch facies, Lower Breccia, Praz de Lys.

There is one feature, however, which can be seen in the rocks, and which may help explain the lack of sole structures in many cases. The material in the breccias is often of cobble grade and always of at least pebble grade. It is unlikely, and there is no evidence to suggest, that such coarse material was carried in suspension. If these breccias were transported as inertia flows (Sanders 1965), as was suggested for the breccias of the breccia facies, it is very likely that a flowing clast-layer was present, at least at the base of the flow. This would protect the substrate from any turbulent eddies capable of forming flutes. Dzulynski and Sanders (1962) suggested such a process for the prevention of formation of flutes in finer turbidites with a 'traction carpet'.

The only other type of bottom structure found in the breccias is a load deformation structure (Plate 18 and FIG. 28). This provides some evidence of the state of sediment cohesion. Two breccias occur in succession without interbeds (FIG. 28A). Most of the material is cobble-pebble grade, but both breccias show grading to sandy material near the top. The lower breccia shows ramifications of sand into the cobbly base of the upper. The structure is believed to be load dominated rather than an erosional structure because the deformed parts of the lower breccia have retained a lamination and grain size segregation which is now aligned parallel to the outline of the deformation (FIG. 28B). This is the only case seen in the flysch facies of two breccias of such an order of thickness (1.70 m and 2.00 m respectively) occurring in rapid succession. The

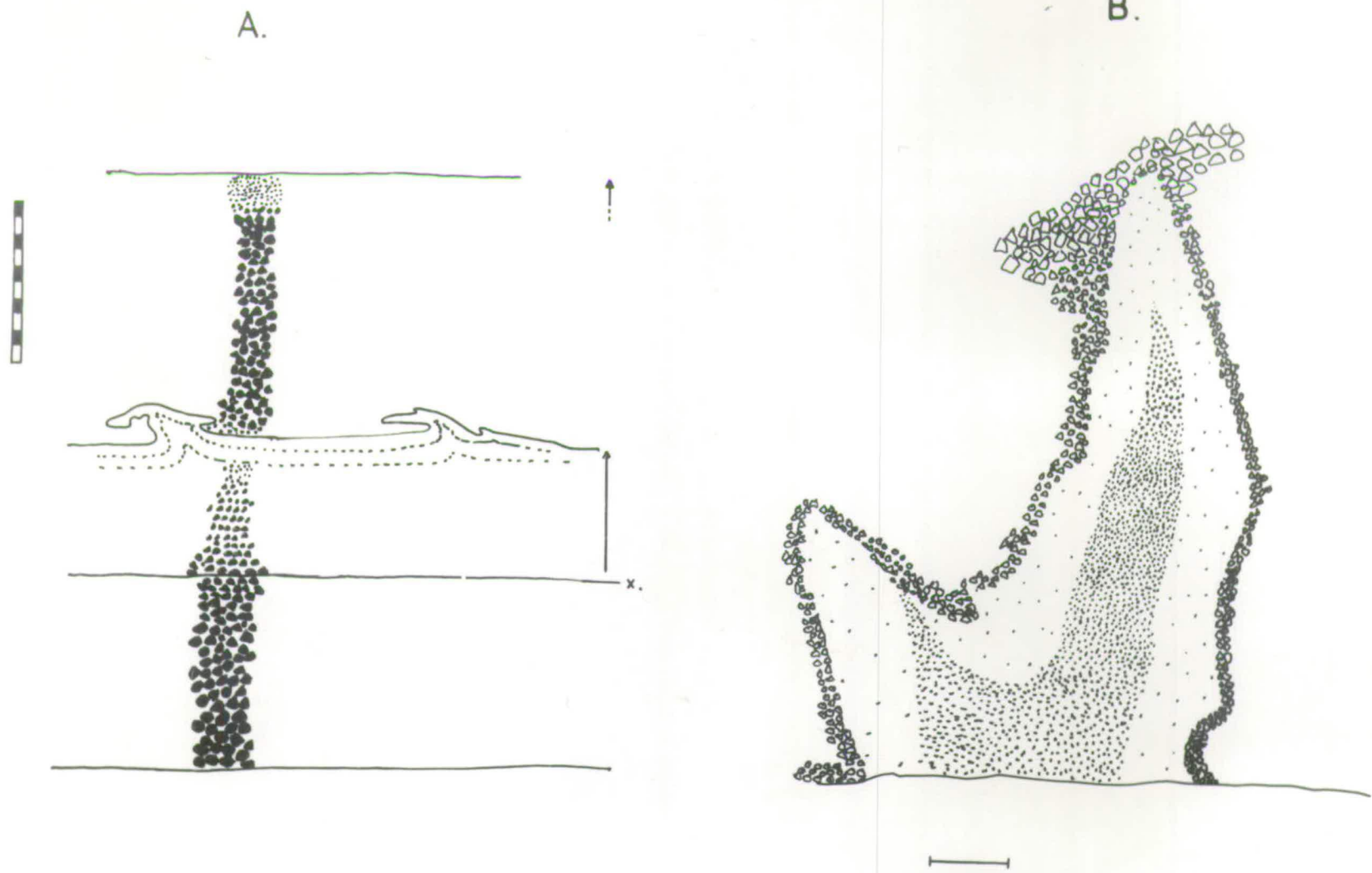


FIG. 28. Load deformation in a breccia of the flysch facies, shown in section, Lower Breccia.
 Scale in A is 1 metre long, and scale in B is 10cm long.

upper one may even be a composite bed - there is a distinct joint plane at 120 cm above the base of the bed, although it is not accompanied by a break in grain size. The uppermost parts of both beds suggest deposition from a waning current (see sequence of sedimentary structures in FIG. 40), and the deformation structures show that at the time of deposition of the upper bed, the underlying sediment was only partially compacted. Since such deformation was not seen elsewhere on the soles of breccia beds, and since breccia beds in the flysch facies do not normally succeed one another, it seems reasonable to conclude that the two breccias here discussed may have had the same origin, so that one was followed (relatively) rapidly by the other before the first had been fully compacted.

Examination of the upper parts of the upper bed shows that deformation has been 'taken up' by internal adjustments in the massive part of the upper bed because no deformation of either the upper boundary of the pebbly part, or the laminations in the sandy part, has taken place.

The significance of the lack of channeling.

In all cases, other than those described above, the bases of the breccia beds are flat and there is no channeling into underlying sediments. Channeling by coarse deposits in turbidite sequences has been reported for example, by Scott (1966), and Walker (1966a). In the case of channeling, the state of cohesion of the sediment surface before arrival of the channel-cutting bed, is not quite so critical as in the case of flutes. Flutes are shallow structures compared with channels,

which may cut down through several of the underlying beds (Walker (1966a)) Below the sediment-water interface, cohesion of the sediment increases with depth. Since channels are likely to cut down to the levels where sediments are cohesive, they are less likely than flutes to be critically controlled by the state of cohesion. Obviously, if the sediment is very fluid for a considerable depth (order of metres) then a channel may not form, but if only the uppermost layers are fluid, then a powerful flow could cut through the upper layers and cut a channel in the cohesive material below.

The reason for lack of channeling in the breccias is considered to be the same as the reason for the common lack of flutes. The large size of most of the clasts would make transport in suspension highly unlikely. The base of the flow would travel as bed-load and as such would have insufficient energy to erode the floor. The channel-cutting beds described by Walker (1967) have a much higher thickness/clast size ratio than the breccias. They could quite conceivably have been transported in suspension, and were obviously capable of deep erosion.

Clast size, and the proportion of very coarse clasts may also be very important in the formation of tool marks. A predominantly fine-grained turbidity current may transport almost all of its grains in suspension. If there are a few large clasts in such a flow, in early stages when the flow has a high velocity, they will be free to follow relatively long trajectories between contacts with the floor as they roll and jump along. Of the energy imparted to such clasts by fluid turbulence, a large proportion would be expended in collisions with the floor,

and perhaps in the formation of tool marks. On the other hand, with a high proportion of large clasts, transport near the base of the flow would be as bed-load, and the likelihood of collisions between large clasts would be increased. In such a case, the potential energy (from fluid turbulence, and a component of gravity) of a tool would be dissipated in clast-clast collisions as well as in collisions with the floor, thus the potential for forming marks on the floor would show a proportionate decrease. In effect, the high concentration of coarse clasts travelling as bed-load 'dampens' the erosive potential of the flow. Thus it is suggested that mode of transport of the breccias, rather than state of cohesion of the material on the sea-floor is the principal factor in the non-formation of channels, and that it may also help explain the lack of tool markings.

There is one occurrence of a case of erosion by a breccia bed. In a thick, granule-grade breccia bed at Avoreaz (Plate 19), rounded lumps of a calcareous mudstone were found near the base of the bed. They are well-rounded, and petrographically similar to the calcareous mudstones in the local succession. They are undeformed, so were obviously sufficiently lithified to abrade rapidly without any plastic deformation in the process. This is the only evidence of penecontemporaneous erosion associated with beds in the flysch facies of the Lower Breccia.

Gravel waves.

Before dealing with the internal structures of the

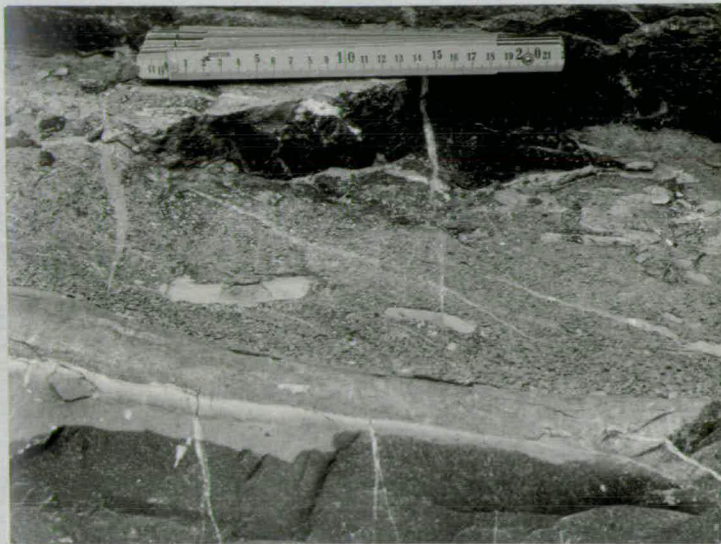


Plate 19. Soft mudstone clasts at base of breccia bed.
Flysch facies, Lower Breccia, Avoreaz.
Scale in cm.



Plate 20. Gravel waves in breccia. Flysch facies,
Lower Breccia, Praz de Lys. Length from crest
to crest is 3-4 metres.

breccias, structures which may be intermediate in character between 'internal' and 'external' will be discussed.

These are the 'gravel waves' found at the top of the massive part of a breccia in the flysch facies of Praz de Lys (Plate 20). They are not strictly 'external' structures because they are in places overlain by sand which is an integral part of the bed. At the same time, since this sand does not cover the wave forms completely, the structures are not strictly 'internal'. The breccia is pebble-gravel grade with no sandy matrix, and the upper surface of the massive portion is deformed into symmetrical waves of length 3.00 to 4.00 metres and height 0.5 to 1.00 metres. (FIG. 29). The crests have a regular orientation and can be traced as far as the outcrop permits i.e. 2-3 metres, and are consistent in orientation and height and length over this distance. Viewed in section they show no internal cross stratification. Above the pebbly part, there is a thin discontinuous sand grade layer, which varies in thickness from 0-7 cm (FIG. 29). This sandy part is graded and has parallel lamination and a poorly developed ripple cross-lamination. The dip of the cross laminae of the ripples in adjacent troughs show opposing directions of flow.

There are three main problems here:-

1. The mode of formation of the wave forms in the pebble-gravel material.
2. The source of the sand which overlies the gravel in places.
3. The mode of formation of the countercurrent, ripple cross-lamination in the troughs of the gravel waves.

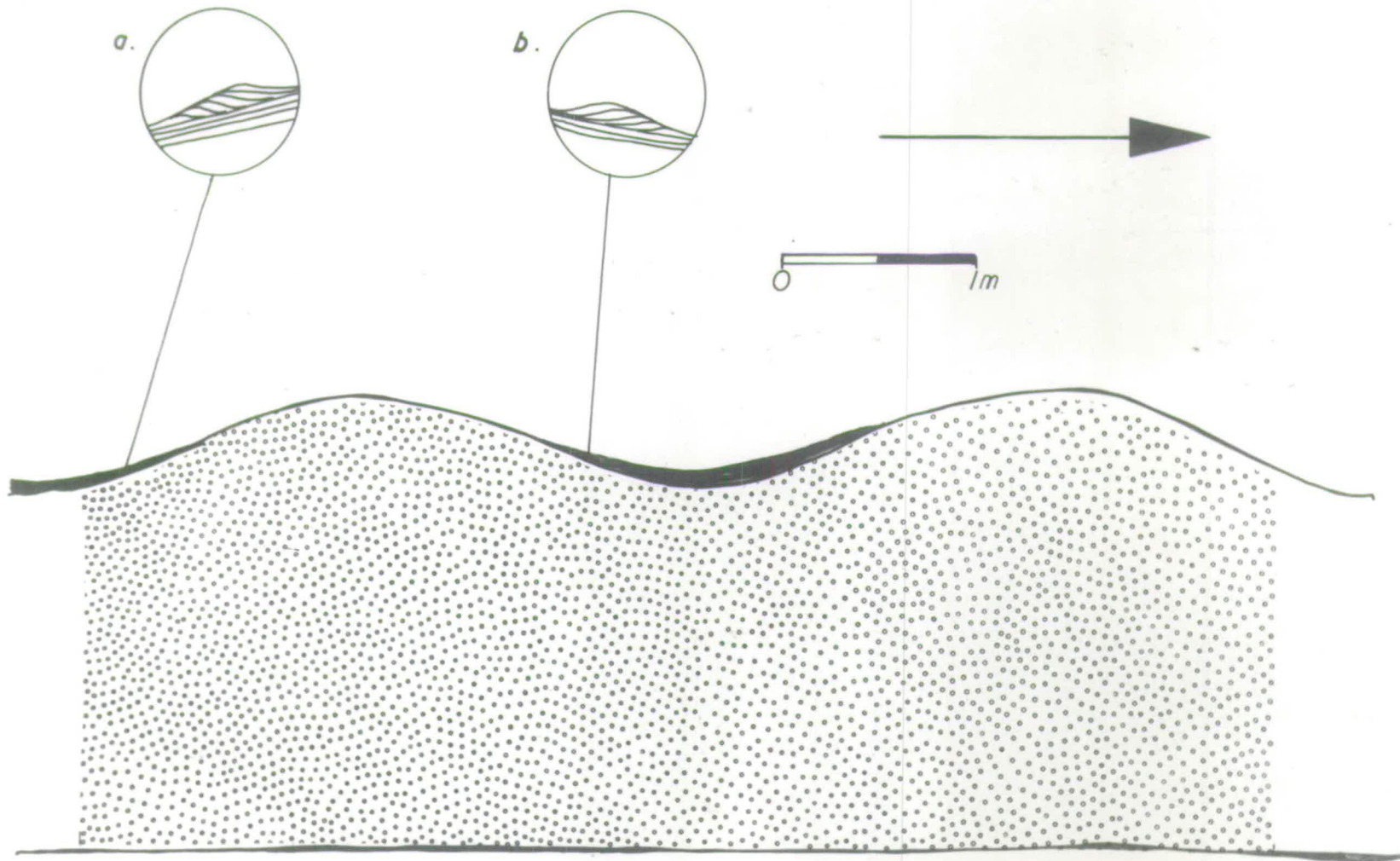


FIG. 29. Gravel waves in a breccia showing normal and regressive ripples. Main current is from left to right.

- the main question being whether or not the structures could have been formed by indigenous bottom currents. The massive part of the breccia is over one metre thick and there are no current structures within it other than an alignment of long particles parallel to the bedding. The wave forms at the top are angular, and lack internal stratification. If the pebbles and cobbles were laid down, and the waves produced by bottom currents it is strange that only the top surface was affected. It would also require strong currents to transport such coarse material. Later deposition of sand would need a reduction in current strength. The massive part of this breccia is not graded but other breccias, just as coarse, in the flysch facies are graded. However, if bottom currents are considered not to be the agents which formed this structure, then it remains to suggest an alternative origin. The lack of internal structures and the coarse nature of the massive part of the bed suggests an origin due to a clast flow as visualized for the massive breccias of the breccia facies. Most of the breccias in the flysch facies are graded up to sand-size material or finer and deposition from turbidity flow was probably important for at least part of the bed. The sand part of this particular breccia is, however, very thin. The following origin is suggested:-

- i) The cobble-pebble portion of the bed was deposited as an inertia clast flow.
- ii) A sandy suspension current may have been directly associated with the clast flow, or if not, it arrived soon after it.
- iii) This turbidity current, travelling at high velocity,

formed waves on the surface of the pebble bed. The gravel waves do not have internal stratification, but the very coarse nature of the material with respect to the scale of the wave form, may have prevented the formation of foreset laminae, although the mechanism of particle transport may have been the same as for dunes. That is, the wave forms must have developed from initial local irregularities on the pebble floor. Formation of cross lamination (foresets) in dunes and ripples is a result of sorting processes operating during selective transport and differential avalanching (Allen 1963a). The large ratio of clast size/form dimensions would limit such sorting.

- iv) As the waves increased in size, captive eddies would form in the trough regions (FIG 30). These would be eddies of a sand suspension in water. Formation of such eddies in the cases of experimental dunes is accompanied by a decrease in flow velocity within the eddies, compared to the region of the main flow above the irregularities of the bed (Allen 1965, FIG. 5). Deposition could take place in the eddy while the rest of the current flowed on above. The bulk of the flow must have flowed on past this locality to be deposited elsewhere. Within the eddies there would be areas of reverse flow (FIG. 30). The laminations, both parallel and cross-lamination would form as the eddy decayed, and those ripples formed where flow was counter to the main current would produce the regressive ripples.

- v) The presence of ripples indicating normal current directions show that re-attachment of separated flow has occurred at a point before the crest of the wave forms (FIG. 30). Deposition at this point also, may have occurred while the bulk of the current passed by, because, as experiment has shown (Allen 1965 FIG. 5), where downstream flow is resumed beyond a dune form, the velocity is reduced.

Since the wave heights here are 0.50 to 1.00 m, and lengths are 3.00 to 4.00 m, the countercurrent path length (Allen 1965) must have been less than 300 - 400 cm to allow formation of normal, downstream pointing ripples.

(ii) Internal structures.

a) Grading.

Many of the breccias are well-graded (Plate 16). Good continuous grading is more common in the thinner beds because the thicker breccias tend to have thicker massive pebble-gravel portions (FIG. 31). The massive portions are generally ungraded except towards their upper limits. Thus those beds with a massive part have grading confined to the upper part, which is generally gravel grade or finer. This can happen on any scale - the bed with gravel waves (discussed above page 41) is ungraded except for a very thin sandy portion at the top. The non-graded nature of most of the massive parts of the breccias, along with their very coarse clasts, are considered to indicate transport as an inertia flow below the turbulent suspension from which the finer grained remainder of the bed was deposited. This upper

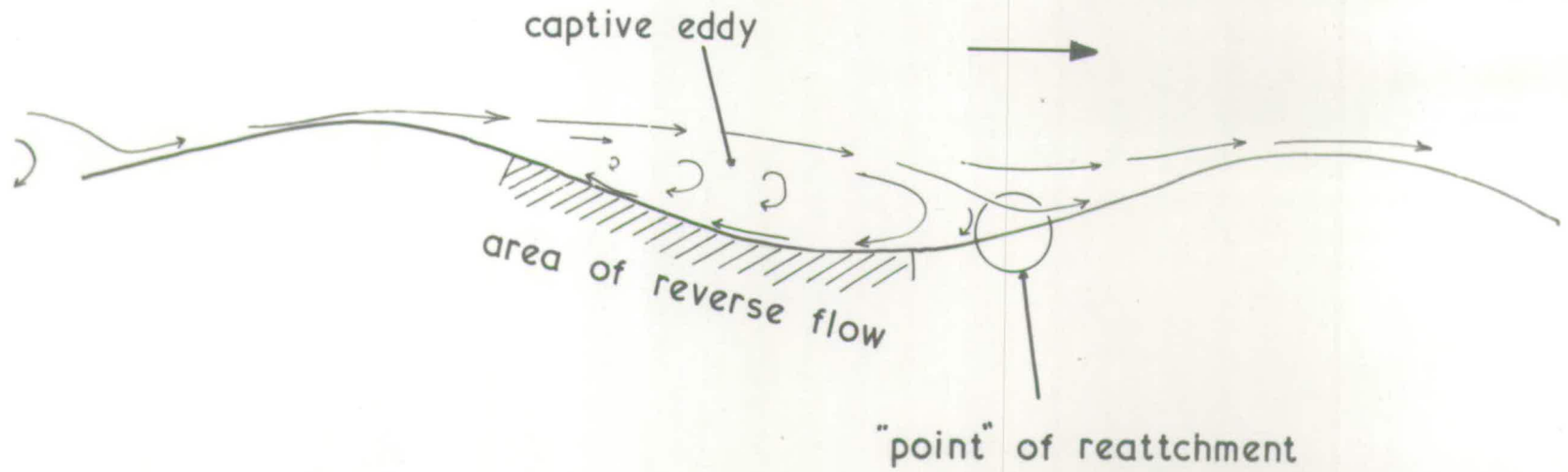


FIG. 30. Generalized flow conditions over gravel wave forms.

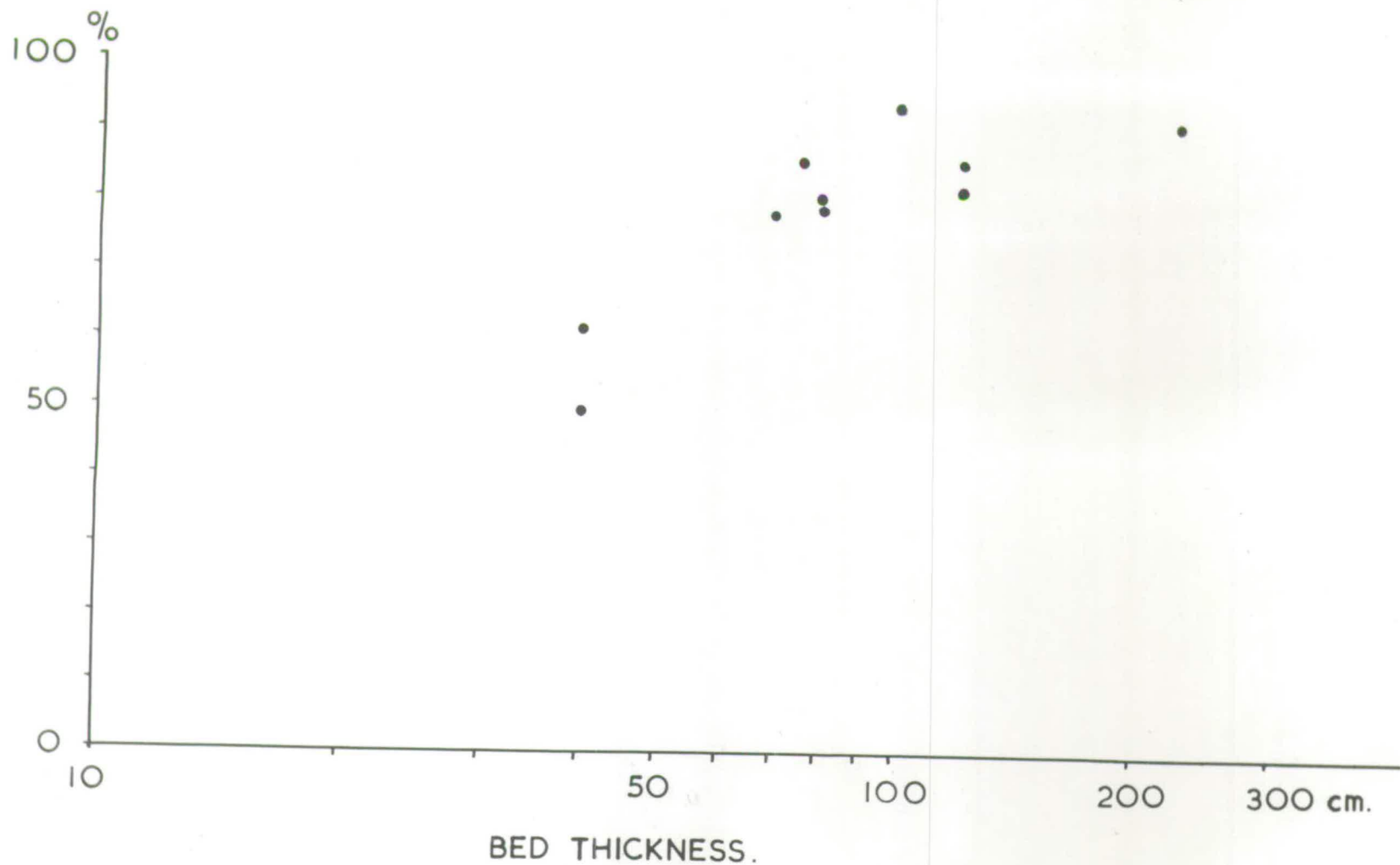


FIG. 31. Breccia bed thickness plotted against proportion of bed which is massive and coarse, flysch facies, Lower Breccia.

part may have a sequence of internal structures similar to those found in turbidites (Bouma 1962). The lower massive part of the breccias is not considered to be analagous to the A division of turbidite beds (Bouma 1962; Walker 1965). The A division of turbidites is thought to have formed by rapid deposition from a turbulent current while flow was in the upper flow regime (Harms and Fahnestock 1965; Walker 1965; Walton 1967). (Flow regime is used in the sense indicated by Simons et al., 1965). In the case of the breccias, deposition of the lower part was from an inertia flow. Where there is a continuous gradation from the lower part of a breccia through to the upper part with a decrease in the proportion of gravel, the flow of the suspension current must have been sufficiently strong to entrain gravel; rapid deposition would have been required to 'freeze' granules in position away from the base of the bed - if deposition was slow, all granules would have separated out as a coarse layer at the base.

The lower massive portions of the breccia beds are generally ungraded. They are not cross-stratified, and in this respect they differ from some of the breccias of the breccia facies. The only structure which is occasionally found in this massive part is an alignment of clasts with their long axes parallel to the bedding.

b) Laminations.

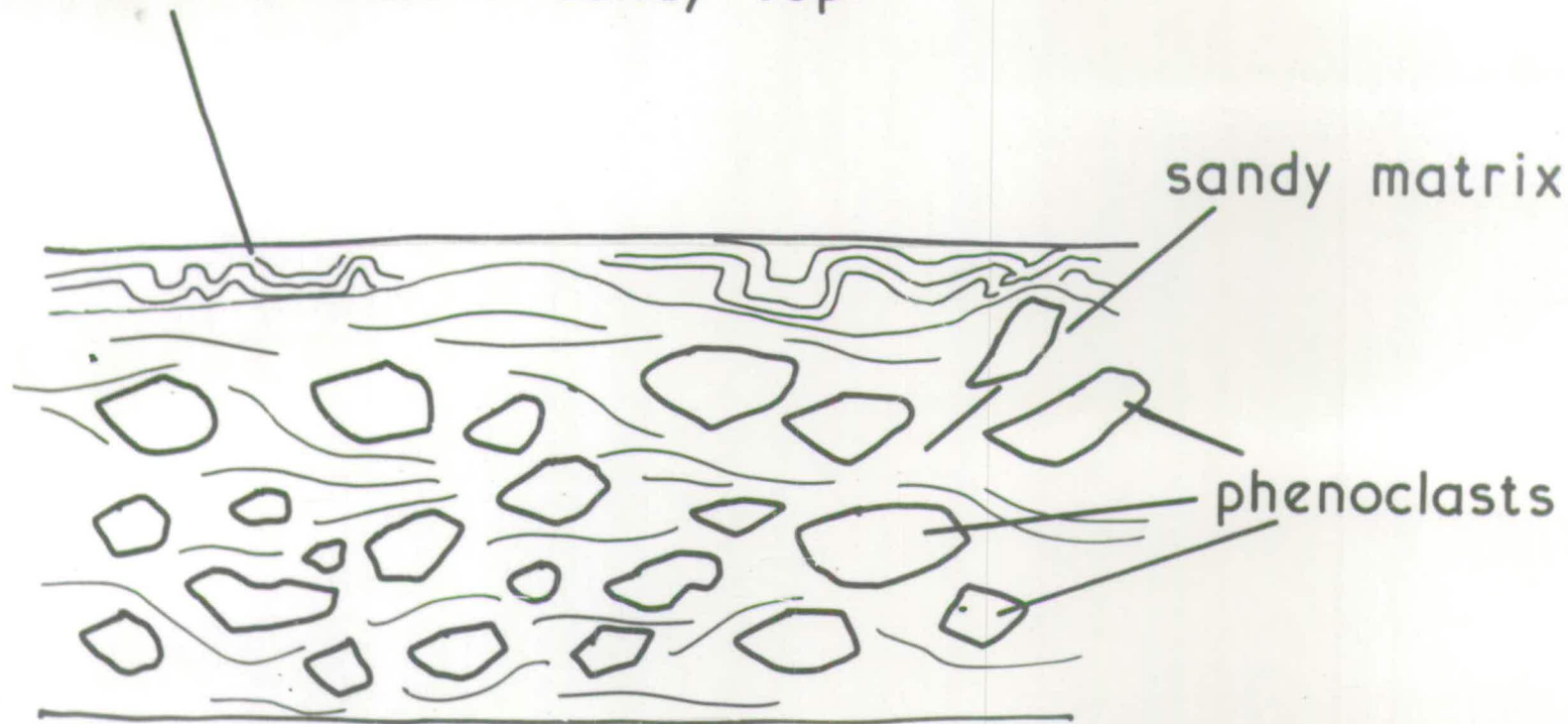
The coarse massive portion of the breccias is overlain, or grades into a sandy, parallel-laminated and/or cross-laminated part which, in turn may (rarely) grade into a silty pelite portion. This upper, sandy part may form from 5% to

50% of the bed by thickness (FIG. 31). With more than 50% sandy and silty material, the bed, by definition, falls into the category of calcilithite. In the upper parts of these breccias parallel lamination is more common than ripple cross lamination. The parallel lamination is formed by alternation of laminae of differing grain size - generally of medium sand with fine sand or silt; it may occur either above or below any ripple cross lamination which is present. The only ripple cross lamination seen at the tops of these breccia beds is rather poorly developed; the ripples are small and in single sets with no climbing or building up of divisions more than one ripple thick.

(b) Chaotic type breccias.

These are much less common than the 'normal' breccias - only three examples are known. They differ from the other breccias in the Lower Breccia Formation in having a distinctly bimodal size distribution. The breccias of this type are 1.00 m to 2.00 m in thickness, they have a large proportion of sandy/silty matrix with pebbles and cobbles scattered throughout the thickness of the bed with no vertical clast size grading (FIG. 32). The upper and lower bedding planes are parallel and planar; the bases of the breccias do not erode the underlying beds. The sandy matrix is irregularly laminated, and wavy. The clasts in these chaotic breccias are identical to those found in the other types of breccia; there are no deformed clasts which must have been soft during transport; these factors, combined with lack of erosion of the underlying beds suggest that an intra-formational origin for the breccias is out of the question.

convolute laminae in sandy top.



1 metre.

FIG. 32. Typical 'chaotic' type breccia, flysch facies, Lower Breccia.

The uppermost part of these breccia beds is sandy and shows intense convolute lamination.

Possible mode of origin.

The irregular lamination in the matrix of these breccias suggests limited internal shear during transport. This favours a slide rather than a flow mode of transport. The rest of the succession shows that there were considerable quantities of very coarse material available in the area, although it did not normally become mixed with sand. Formation of the chaotic type breccias must have involved mixture of the two grain-sizes before the final period of transport. Alternatively, mixture of the sediment may have occurred during transport, possibly as a result of a slide of interbedded gravels and sands.

It is difficult to see whether the sandy top of this type of breccia formed an integral part of the slide which deposited the main part of the breccia, or whether it is another bed which was deposited on top of the breccia and formed convolutions during deposition or compaction because it had been deposited on a very uneven surface.

2. Calclithites.

The calclithites are predominantly sand-grade graded beds, with varying proportions of gravel. They are generally much thinner than the breccias of the flysch facies and have an average bed thickness of around 10 cm; rarely they are found up to 200 cm in thickness (FIG. 33). An arbitrary, lower, thick-

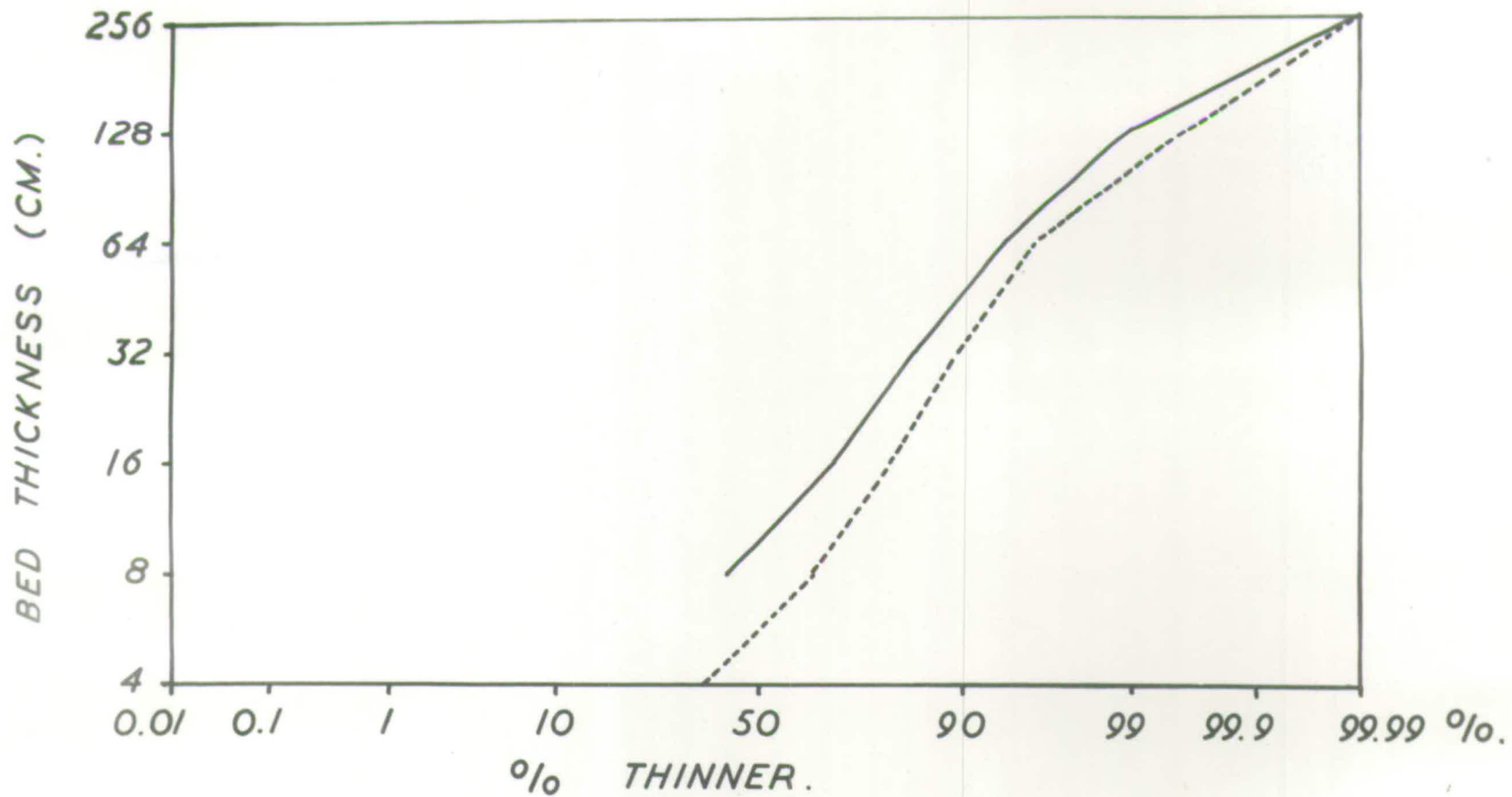


FIG. 33. Cumulative frequency/calclithite thickness curves for flysch facies (dotted line), and for those calclithites which are thicker than 5cm (continuous line).

ness limit of about 5 cm is chosen for the calcilithites. Below this thickness beds of similar grain size and composition occur but they are rarely isolated; they are part of the calcilithite-pelite units (see p. 74).

The beds are planar and extend with more or less constant thickness for the length of any one outcrop. Several graded calcilithites may succeed each other, or they may be separated by either breccia beds or calcilithite-pelite units. The proportion of calcilithites in any measured section varies from less than 20% to as much as 100%.

a) Sedimentary structures in the calcilithites.

The following sedimentary structures are found in the calcilithites:-

b) External structures.

- 1) Flute markings.
- 2) Other sole markings of doubtful nature.

c) Internal structures.

- 1) Grading.
- 2) Dune cross-lamination.
- 3) Ripple cross-lamination.
- 4) Parallel lamination.
- 5) Convolute lamination.

b) External structures.

- 1) Flute markings.

Only a few calcilithites with flute markings were seen. The flutes are poorly developed and ill-defined. The pelite which forms the topmost parts of other graded calcilithites,

and which occurs in the calclithite-pelite units is silty-pelite rather than clayey-pelite. The higher the silt content of a clayey sediment, the longer it takes for the sediment to attain cohesion (Postma 1962), so it is possible that the sediment may not generally have been sufficiently cohesive for the preservation of flute marks, or even for their formation. Exposure of the bottom surfaces of beds is not widespread because of the attitude of the beds, but of the flute markings seen, none were really good examples.

2) Other sole markings of doubtful nature.

These are variable in size and generally roughly flute-like in shape (Plate 21). They form depressions on the lower surfaces of calclithite beds which are filled with sediment slightly coarser than the rest of the bed (Plate 22). With some examples, an upstream and downstream end can be determined.

c) Internal structures.

1) Grading.

Most of the calclithite beds show a grain size grading from bottom to top. The description of grading is difficult, although several attempts have been made (Kuenen 1953; Ksiazkiewicz 1954; Walton 1956; Birkenmajer 1959; Scott 1966).

In the calclithites of the flysch facies, the following types of grading are found:

- 1) Normal, continuous grading from bottom to top of the bed, with no other structures - at least for most of the bed (Plate 23).



Plate 21. Large flute-like scour on base of calclithite.
Flysch facies, Lower Breccia, Les Lindarets.



Plate 22. Coarse material in sole marking. Flysch facies,
Lower Breccia, Les Lindarets.

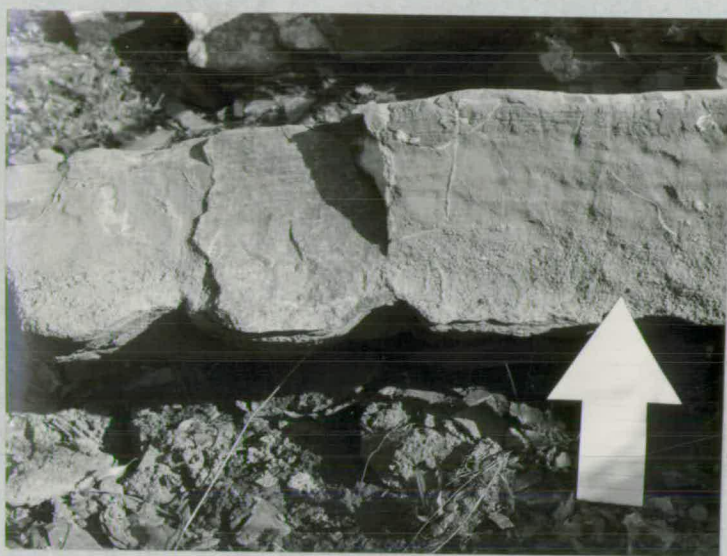


Plate 23. Grading in calcilithite bed. Flysch facies, Lower Breccia, Pont des Gets. Arrow is 15 cm. long.

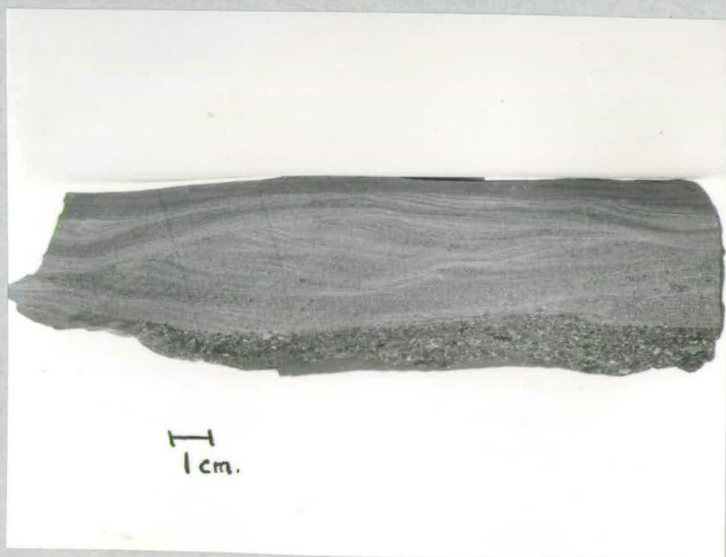


Plate 24. Thin graded bed with structures. Flysch facies, Lower Breccia, Praz de Lys.

- 2) Continuous grading for part of the bed only, usually the upper part (Plate 16).
- 3) Grading through a bed with sedimentary structures (Plate 24).

At the boundaries between the different types of structure there may be grain size breaks, giving interrupted grading (Walton 1956).

The most striking type of grading is the first type which is at the same time the least common (cf. Scott 1966 page 80). Grading which is normally recognized in the field as 'good', is most obvious in those beds without internal structures. This is because grading in a bed is to a certain extent 'masked' if there are internal structures in the bed e.g. see Plate 24. The principal difficulty involved is the lack of any quantitative measure of grading - the only quantitative analysis of grading which has so far been described (Dahlberg and Griffiths 1967) is too complicated to apply on a large scale in the field. However, there may be a real difference in that better grading is developed when other internal structures are absent. Certainly, in such a case, it is the depositional process alone, controlled largely by gravity, which produces the grading. On the other hand, if internal laminations are being formed, other sorting processes are taking place in the horizontal and inclined planes as well as in a vertical direction. This is bound to have an adverse effect on the degree of 'perfection' of the grading. Evidence from experiments in the formation of graded beds (Kuenen 1966a) showed that in many but not all, cases, internal lamination was present where good grading was absent, and vice-versa.



Cross lamination.

There are two types of cross lamination found in the calcilithites of the flysch facies. The first is found in gravel grade material at the base of certain beds, and has the dimensions of dune structures - for this and other reasons given below, it is named 'dune cross-lamination'. The second type is ripple cross-lamination.

2) Dune cross-lamination.

The dune cross-lamination occurs in dune-shaped wave forms with flat bases, the lamination never fills hollows. The dunes are found in the lowermost parts of some of the graded calcilithites (Plate 25). In a section measured at Praz de Lys, dune structures were found in about 8% of the beds. The structure generally involved pebble and granule grade material. Other beds with these grain sizes do not have dune structures. The dunes are sometimes isolated. Dune length is from 200 cm to 700 cm, and dune height is from 5 cm to 15 cm (FIG. 34). The upper surfaces of the dunes show a sharp contact with overlying finer material which is generally rippled, rippled and convoluted, or parallel laminated (Plate 26).

The most striking feature of the dunes is the very coarse nature of the material. The other report of dunes in turbidites (Hubert 1966) involves similarly coarse material. All of the occurrences here show a marked grain-size break, of the order of pebble or granule to coarse or medium sand. Dunes are formed by the bed transport of material in an intermittent fashion with particles carried up the stoss slope by the current, followed by

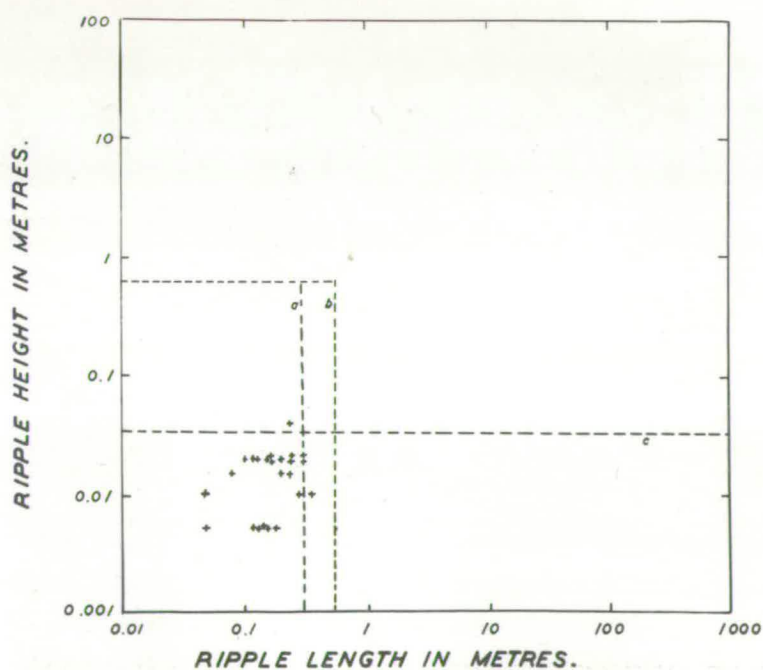
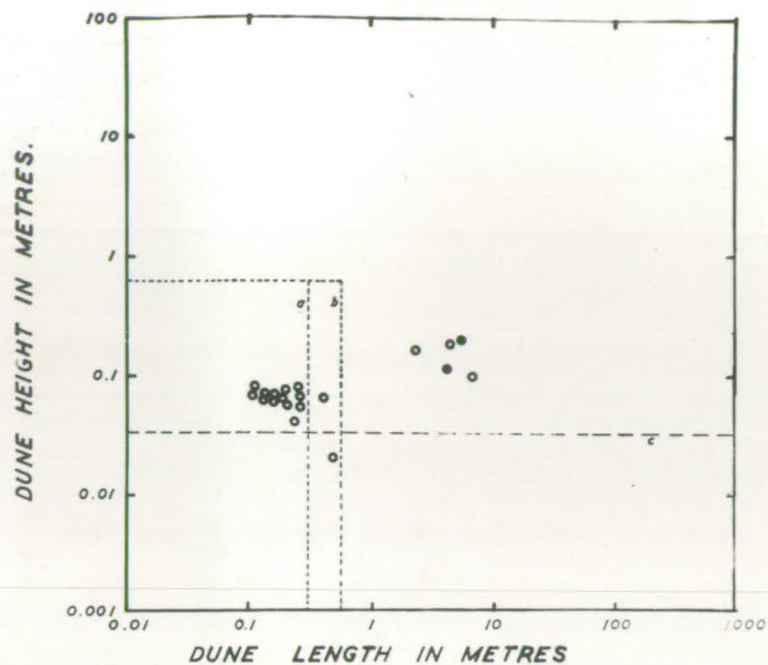


FIG. 34. Length/height for dunes (top) and ripples (bottom) in calcilithites, flysch facies, Lower Breccia. Open circles - dunes in the flysch facies; solid circles - dunes in Whitehouse Fmn., Girvan (Hubert 1966); crosses - ripples in the flysch facies.



Plate 25. Dune form at base of graded calcilithite.
Flysch facies, Lower Breccia, Praz de Lys.
Pen is 13 cm long.



Plate 26. Parallel lamination overlying dune form in
graded calcilithite. Flysch facies, Lower
Breccia, Praz de Lys. Pen (14 cm long) is
parallel to cross lamination in dune.

sliding or avalanching down the lee slope to form foreset laminae. Because of their relatively large size they require more time to form than do ripples. They form in the upper part of the lower flow regime (Simons et al., 1965).

Since those beds with a dune form show a marked grain-size break at the top of the dune form, the following mode of origin is suggested. The initial turbidity current had a considerable amount of gravel which was deposited early in its course. The rest of the material, medium - fine sand and silt, remained in suspension and flowed faster than the carpet of coarser grains. Flow above the current was powerful enough to move the coarse grains in the dune phase of transportation. With further deceleration, the dunes stopped moving, and they were preserved because the material was too coarse to change to ripples, even if there had been sufficient time available. The rest of the current then deposited its load on top. A similar situation has been described by Kuenen (1967) from experimental studies. When he tried to simulate formation of a traction carpet, he found that the carpet which did form moved so much more slowly than the current that waves formed along its surface.

Consideration of turbidite beds in general shows that dunes are the exception rather than the rule. Walker (1965), Hubert (1966) and Walton (1967) have suggested that the following factors may have been important in deciding whether or not dunes could form by deposition from a turbidity current:-

1. Depth of flow.
2. Presence of fine sediment.
3. Grain size unsuitable for dune formation.
4. Lack of sufficient time for dune development.

The bearing of each of these factors on the formation of dune structures, in light of the present study, is dealt with below:-

1. The presence of dune structures in some turbidites proves that in certain cases, the depth of flow was suitable for their formation.
2. With regard to the influence of fine sediment, the dunes in the Lower Breccia Formation contain no mud, the finest material in the dunes is sand material but the bulk of the material is granule grade and coarser. Experiments have shown (Simons et al., 1965) that a concentration of 25,000 ppm of clay can inhibit the formation of dune structures in medium sand, by increasing the dune length and decreasing the height. Kuenen (1966b) has suggested that the initial lutum content of many turbidites may be of the order of 0 - 100,000 ppm - sufficient to achieve the required effect if the laboratory conditions can be extrapolated to the processes operating during turbidite deposition. However, the opposite effect, i.e. an increase in the angularity of the dunes, is obtained in the experimental case if a bed material with a greater fall

velocity is used (Simons et al., 1965). As has been noted above, the dunes in the turbidites here consist of very coarse material. I would suggest that in the present case, the effect of large grain size has been more important than the effect of any fine sediment which may have been present.

In many turbidites, however, the coarsest material present is medium to fine sand, and the presence of mud may well prevent formation of dunes in such cases. Thus, the suggestion of Hubert (1966) to this effect is possibly of great importance in the case of many finer-grained turbidites.

3. The chart produced by Simons and Richardson (1966) showing how stable bed form varies with flow power and size of bed material (FIG. 35) has a very small range of flow power over which dunes are the stable bed form when the bed material is small. FIG. 36, derived from this chart, shows how the range of flow power over which dunes are a stable bed form, increases with increase in the median fall diameter of the bed material. For fine material, the current would pass through the range of flow power over which dunes are stable, very quickly, unless the deceleration was very slow - thus, ripple formation would be favoured. However, with larger grains and a similar deceleration rate, there would be more time available

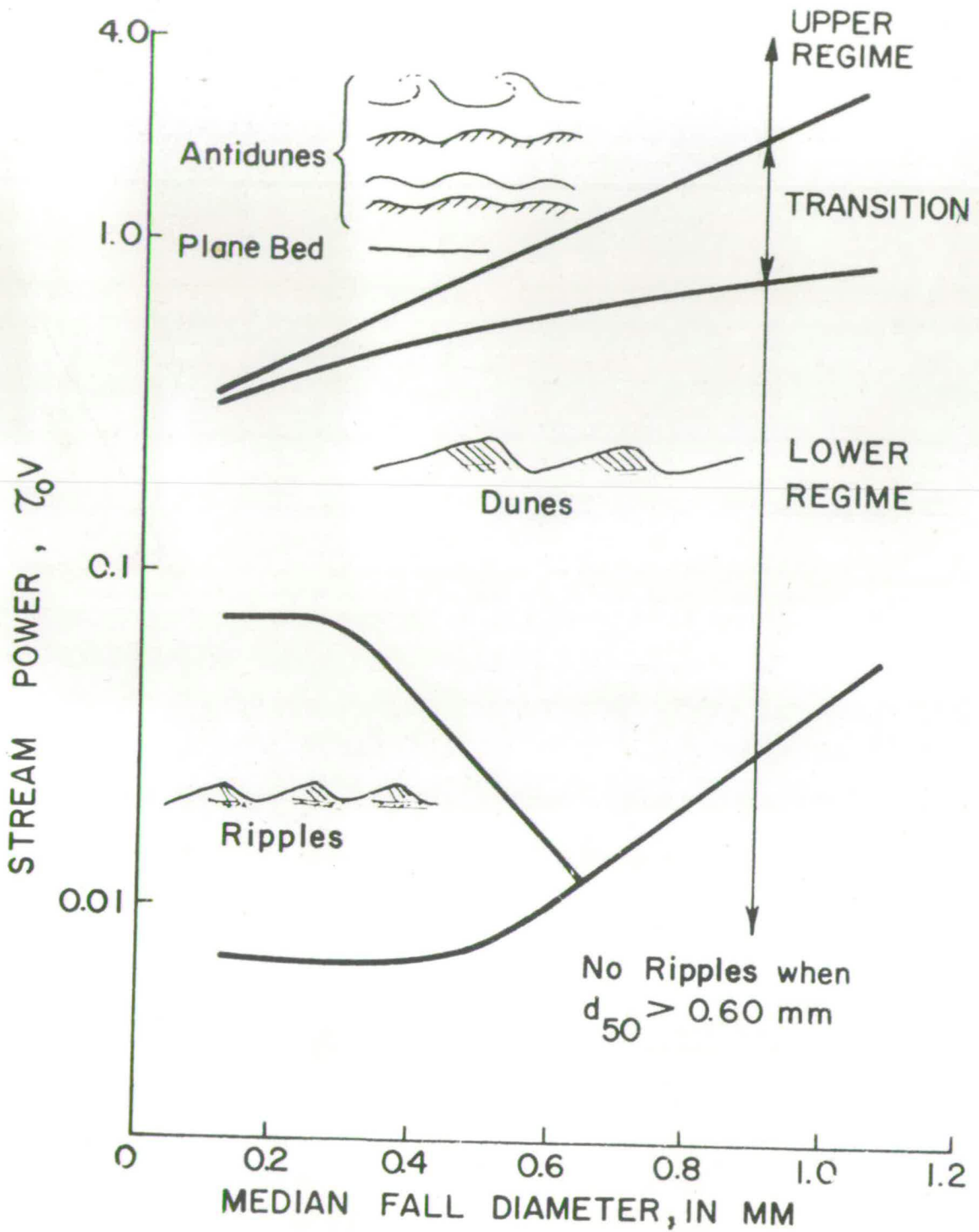


FIG. 35. Grain size/flow power diagram (after Simons et al 1965).

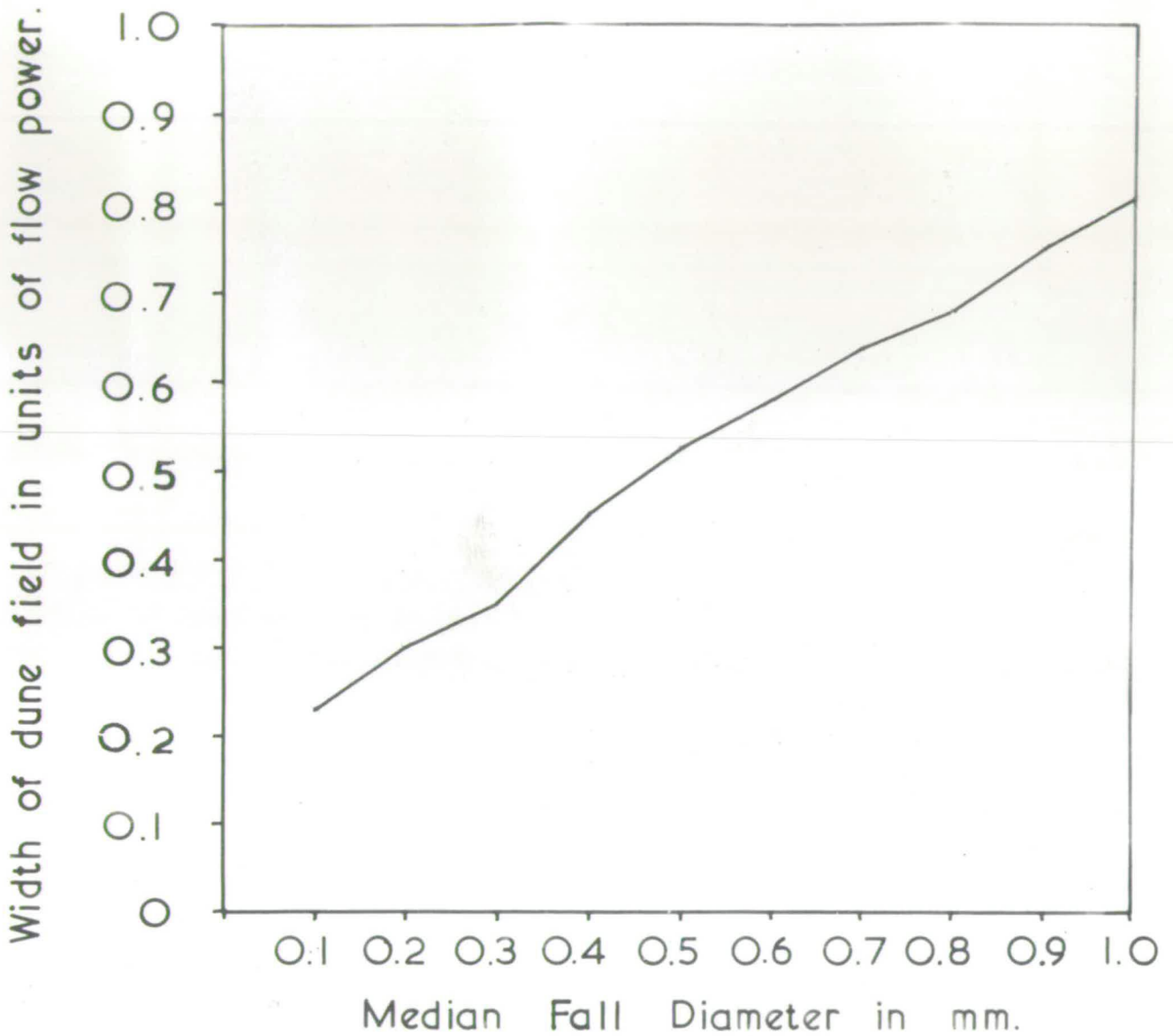


FIG. 36. Diagram derived from the data of Simons et al (1965) showing how the size of the dune field increases with the grain size of the bed material.

for the formation of dunes. This assumes that their development is not arrested by rapid burial. The small size of the stability field for dunes at small grain sizes is the explanation offered by Allen (1969) for the common absence of dunes in turbidites. A further factor which aids formation of dunes in coarse rather than fine material is that if the material in which the dunes form has a median fall diameter less than 0.6 mm, with continued decrease in flow power the bed form may change to ripples (FIG. 35). However, if the material is coarser than this, then this transition cannot take place, because ripples can form only in material with median fall diameter less than 0.6 mm. (Simons and Richardson 1966).

4. Time available for the formation of dunes depends on the rate of deposition which in turn depends on,
 - a) The rate of deceleration of the current.
 - b) The grain size distribution within the current.

If deceleration is very fast, deposition will be fast or even sudden and no structures, except perhaps grading, will develop. With a slower rate of deposition and continuous fall out of material, dunes may not be able to build up, and ripples, because they are smaller scale structures, or parallel laminations may be favoured. Since dunes are, by definition, larger structures than ripples they require more time for their formation. Although ripples may form during fall out of material from a turbidity current, under similar conditions, dunes would be

buried at a very early stage in their development. This would mean replacement of dunes by either parallel or ripple cross-lamination - in most cases the dune would have been no more than a potential structure in that an actual dune form would not develop. Development of a dune, even one which would later change to ripples, would need a limitation to further deposition while the dune structure was in the process of formation. If deposition were continuous, there would be a continual change in the grain size of the material on the bed, and new material would be arriving all the time. These factors would not favour build-up of structures the size of dunes. However, if the current had a bimodal grain size distribution with an excess of coarse grains then deposition would take place in two distinct episodes. First, the coarse grains would separate out, then there would be a period of non-deposition before the rest of the current was deposited. Thus, with uniform deceleration rate, the grain size distribution could produce a non-uniform deposition rate. This would produce the required lull in deposition to allow the build-up of dunes, and at the same time the coarse material, which was laid down in the first phase of deposition, would be most suitable for both the formation and the preservation of dunes as described in part 3 of this discussion.

To summarize, the main conditions for the formation of a dune division are:-

- 1) Early separation of suitable sizes of material in sufficient quantities for dune formation.
- 2) A period of non-deposition to allow the dunes to build up.

Preservation of the dunes is favoured if:-

- 1) The grain sizes are too coarse to make the transition to ripples.

or

- 2) Dune formation is followed by a sudden rapid deceleration of the current with consequent burial of the dunes. If fine material (less than 0.6 mm median diameter) was being moved as bed-load, and there had been a period of non- or low-deposition to allow formation of dunes, there would have to be either a sudden rapid deceleration to prevent the change from dune to ripple bed-form, or, a sudden deceleration and burial of the dunes by mud. I can see no reason why there should be such a rapid deceleration after a period of very low deceleration rate. It seems likely, therefore, that dunes formed in fine and medium sand deposited from a turbidity current would have time in which to make the change to a rippled bed-form. The most favourable conditions for dune formation would all be fulfilled when there was a suitable proportion of gravelly material in a predominantly sandy current. Since the majority of turbidite sequences have little gravel, it is most likely that dunes would tend to occur only in those sequences with considerable amounts of conglomeratic and gravelly turbidites.

Early stages in the development of dune structures.

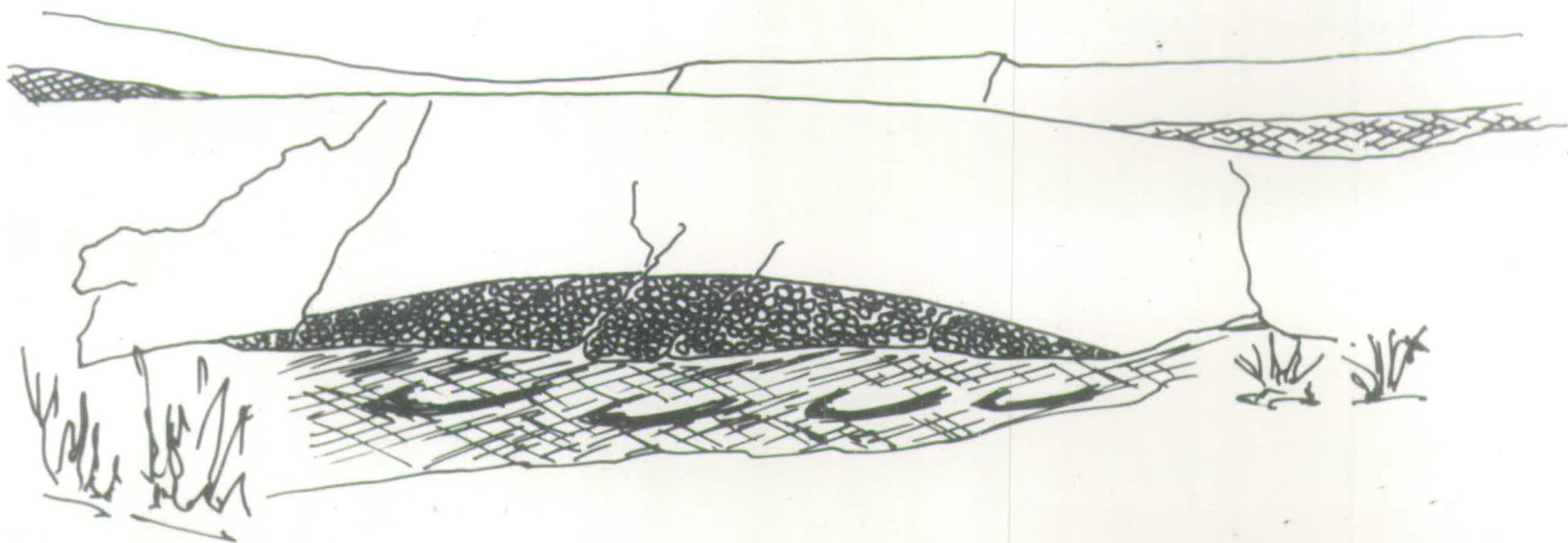
There are cases where wave shaped gravel bodies in the calcilithites show no internal cross stratification. These are of low height and long chord length compared with dunes (FIG. 37). Their low relief and lack of internal lamination suggests that they may represent an early stage in the development of dune structures. From an initially fairly uniform spread of gravel on the floor, there may be a progression through this low relief structure to the full cross-laminated dune-form, much in the same way as desert dunes develop.

Comparison with other occurrences of dunes in turbidites.

The only other reported instance of dunes in turbidites is in the Whitehouse Formation, Girvan (Hubert 1966). The dunes in this case are similar in both dimensions and grain size to the dunes found in the Breccia Nappe (FIG. 34 and Plate 27). They are composed mainly of carbonate material - principally shell debris as opposed to the lithic material found in the Breccia Nappe cases. Although it is more likely that bioclastic material may be found in granule-pebble size material, the fact that the Breccia Nappe examples contain rock fragments in this size-range suggests there should be no reason why dune structures should not be found in turbidite sandstones, so long as the coarse material is present in suitable quantities.

3) Ripple cross lamination.

The second type of cross lamination occurs in sand/silt-grade material (FIG. 38) and represents the C division



10cm.
I

FIG. 37. Presumed early stage of dune formation in calcilithite at Les Lindarets, flysch facies, Lower Breccia.



Plate 27. Dune form in a graded limestone of the Whitehouse Fmn. (Ord.), at Girvan, Scotland. Pen (13 cm) is parallel to the cross-lamination.

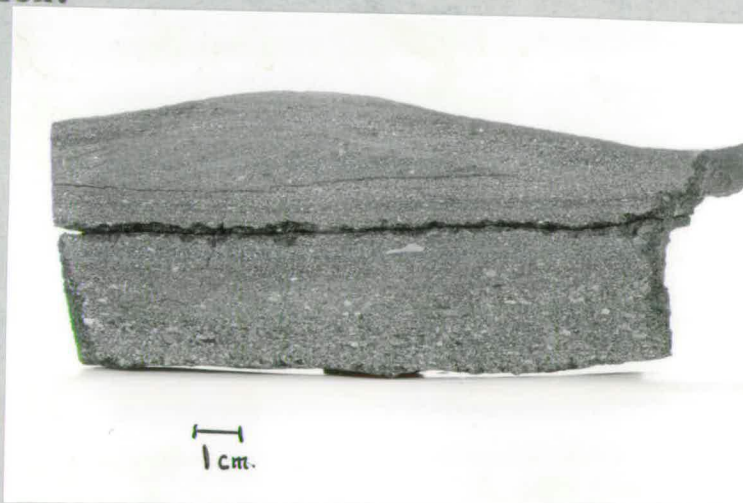


Plate 28. Graded bed with solitary rippled division. Flysch facies, Lower Breccia, Praz de Lys.

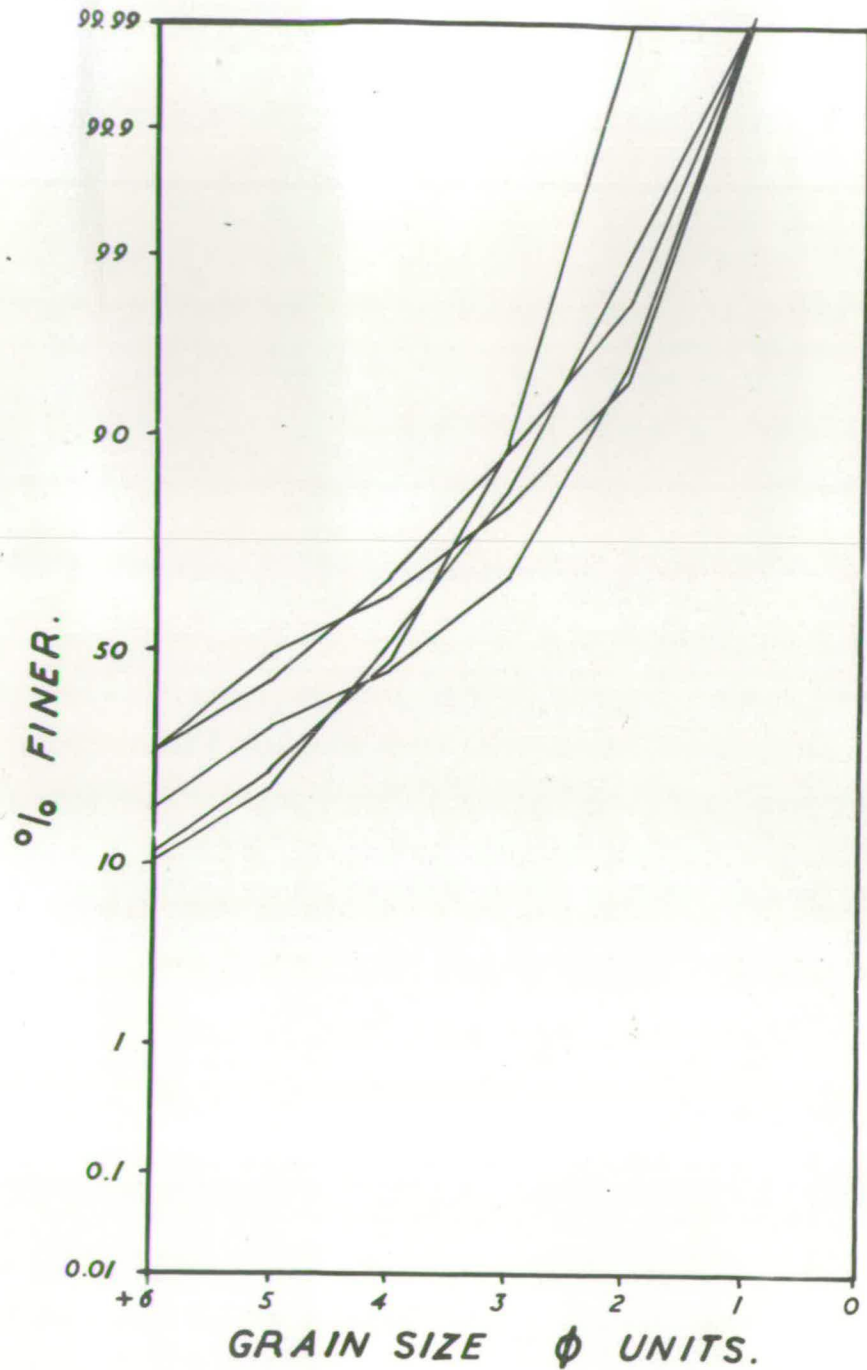


FIG. 38. Cumulative frequency/grain size curves for some ripples in calcilithites, flysch facies, Lower Breccia.

The data are uncorrected and derived from point count analyses.

(Bouma 1962) of the turbidites. The ripples may be in solitary (Plate 28) or grouped units (Plate 29). Most of the C divisions are thin (FIG. 39) and thicknesses built up of more than one or two sets of ripples are rare. Sets of climbing ripples were not seen.

The difference between dunes and ripples.

A comment on the difference between dunes and ripples may be in order here. The distinction has been rather vague but is usually determined on the basis of scale, with an upper limit of about 2 cm height for ripples (Potter and Pettijohn 1965). A plot of ripple length against ripple height for the dimensions of all published accounts of ripple and dunes, showed a distinct lack of values around length = 35 cm, and height = 3.5 cm (Allen 1963). In flume experiments with sand, ripples do not form if the median fall diameter of the bed material is greater than 0.6 mm (Simons et al., 1965). The values for ripples and dunes in the flysch facies of the Lower Breccia were plotted (FIG. 34). They show a spread into the gap between the large scale and small scale ripples of Allen (1963b) (FIG. 34 line c). The values also spread between the fields of ripples and dunes (a - upper limit for ripples, b - lower limit for dunes) according to Simons et al., 1965.

Since the data presented here do not fit into any one of the two categories, the dimensions of these cross-stratified wave forms cannot be used to label them as either ripples or dunes. Instead, the two types are identified by the grain

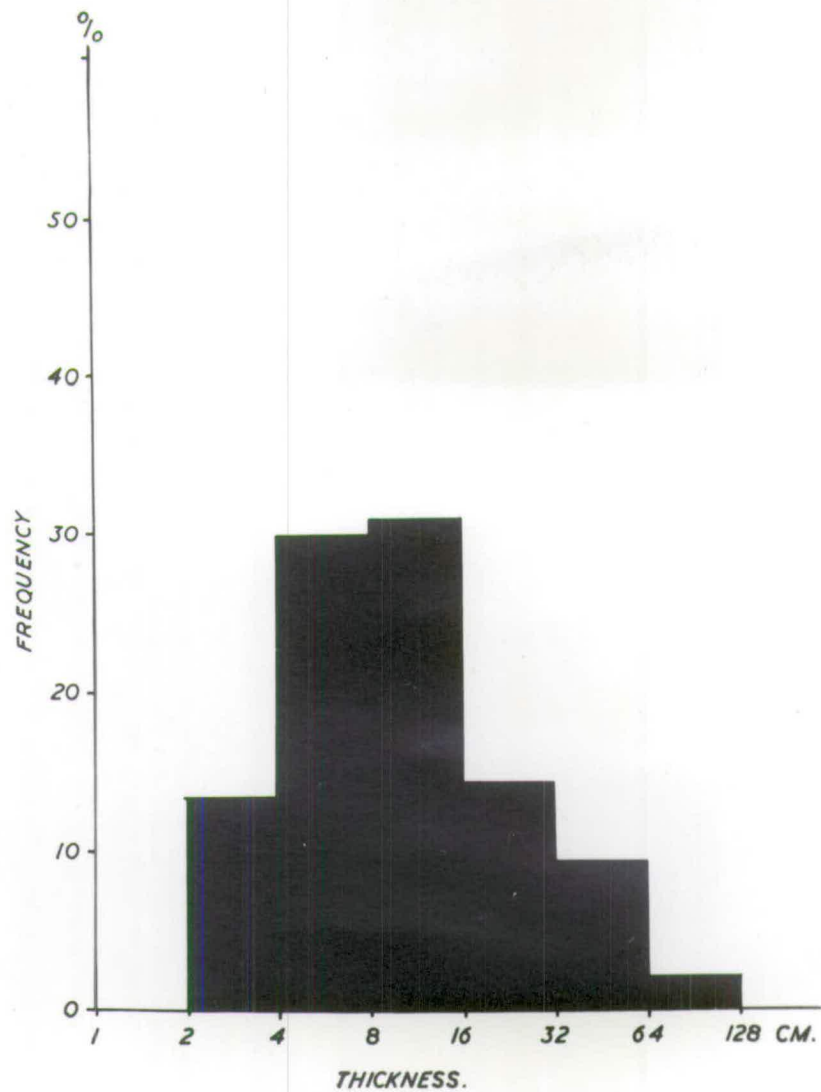
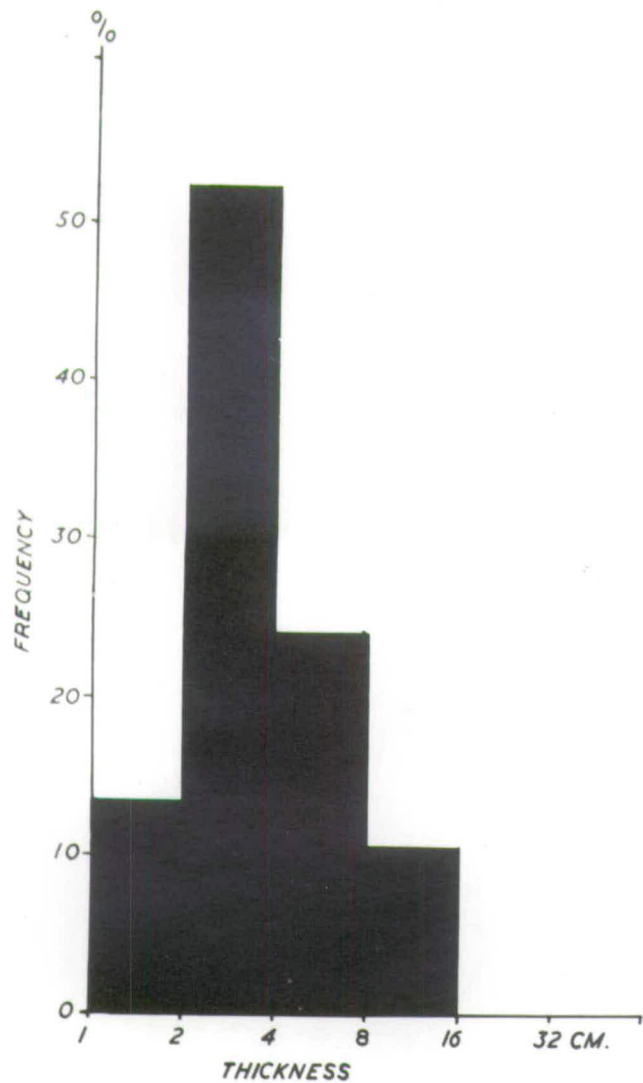


FIG. 39. Frequency%/thickness histograms for C divisions (on left), and B divisions (on right), from calcclithites, flysch facies, Lower Breccia.



Plate 29. Grouped ripples in C division of a graded
calclithite bed, Flysch facies, Lower Breccia,
Avoreaz.

sizes involved. Fortunately, most of the larger forms are composed of granule-pebble grade material and these are considered as dunes, while the structures in the sand and silt material are considered ripples - these are generally smaller scale. Classifying the structures on the basis of grain size means that the only difference between the dune/ripple boundary of Allen (1963b) and Simons et al., (1965) and that of the present case is that the upper size limit for ripples is slightly greater.

Environmental significance of the dune structure in turbidites.

The very coarse nature of the breccia deposits suggests a near-source environment, and the other report (Hubert 1966) of a dune structure in turbidites was in a coarse, near-source sequence. From hydraulic considerations (described above), the availability of coarse material is thought to be an important factor in the formation of dune structures in turbidites. Added to this, any turbidity flow which is carrying gravel will tend to deposit the gravel early in its course - unless the gravel forms a very minor part of the flow, when it may be carried in the body of the flow for a considerable distance before deposition. In this latter case, it is unlikely that there would be a sufficient quantity of gravel present to form dune structures. In addition to a suitable supply of gravel, the current must have enough power to transport it in the dune phase of transport. Neither of these conditions are likely to be fulfilled further out in the basin because the strength of the current will have fallen off and the coarsest material will already have been deposited. Even if there were a source of gravel far out in

the basin, only very powerful currents would be able to transport it as dunes.

It is therefore considered most likely that a dune structure in turbidites will normally only be found in a proximal or ultra-proximal environment, and will usually be associated with coarse deposits.

Introduction of the gravel by a turbidity current rather than a normal bottom current is considered essential. Gravel material in the flysch facies is found in breccia beds, and at the bases of graded calcilithites either as a layer or as a dune structure; it is occasionally found as very small quantities throughout the thickness of a single graded bed. The dune cross-stratification is never found built up beyond the thickness of one dune; the breccias are not cross bedded; thick beds of gravel and coarser material with continuous or intermittent cross stratification do not occur. These are features which would be expected if bottom currents had played an important part in deposition of the gravel and coarser material in the flysch facies. Formation of the thick sequence of graded deposits by bottom currents would require that bottom currents capable of introducing and forming dune structures in gravel material, should wane during the deposition of sand, silt, and finer grained beds. By contrast, the habitual occurrence of the dune structures at the basal parts of graded beds, the common grading of the beds, and the lack of traction structures in the other gravel deposits (i.e. breccias) of the flysch facies, favour the deposition of dune gravel from turbidity flows and the formation of the structures by the flow of the turbidity current

4) Parallel lamination.

Parallel lamination in turbidites is one of two types:-

- 1) A lower (B) division of parallel lamination with
 - a) Alternate laminae of different composition and/or grain size
 - or b) A lamination produced by the parallel alignment of grains and no alternation of different grain sizes.

Parting lineation is found on the lamination planes in this type.

- 2) An upper (D) division of parallel lamination in much finer material than is found in the lower division (silt-grade material). It is a result of alternate laminations of slightly different grain size or composition.

Type 1b has not been found in the Breccia Nappe, but the other two types have. If a parallel-laminated bed has no current-ripple lamination then it is impossible to tell where the B division ends and the D division begins, short of making a grain size analysis. In general, if the parallel lamination is in silty pelite material, it is considered to be a D division; if it is in gravel, sand, or sandy silt, it is considered to be a B division. Most of the parallel lamination seen is of the B type. It is most commonly around 10 cm in thickness but can reach thicknesses of up to a metre (FIG. 39). The lamination in these B divisions does not show parting lineation on the lamination planes, and it is always either a grain size or mineralogical change which marks the lamination. Although this is not the type of lamination attributed to formation in the

lower part of the upper flow regime by Walker (1965), it occurs at the same position in the bed. Kuenen (1966a) conducted experiments in a circular flume where parallel lamination and cross lamination were produced by deposition from a decelerating muddy current. The parallel lamination always occurred below the ripple cross lamination, and it was a result of the alternation of either different grain sizes, or grains of different mineralogy. Kuenen considered the lamination to have formed by a 'like seeks like' process, so that grains with similar size or composition formed patches, and, as deposition progressed these patches built up to form laminae. The important point is that since the current was decelerating, the parallel lamination always formed at higher flow powers than did the cross lamination. It may not be a valid comparison to consider that a B division of the type 1a (above) can be explained by deposition in the upper flow regime (plane bed with sediment movement) of Simons et al., (1965)

This type of lamination, in material of coarser grain than 0.2 mm, does form however, at higher flow power than ripples so that the sequence of internal structures in turbidites described by Bouma (1962) can still be interpreted in terms of decreasing flow power of the current, but not necessarily in terms of the flow regimes of Simons et al., (1965).

Approaching the problem from the opposite direction, a similar conclusion is reached. If a graded bed is considered to have been deposited from a gradually waning current, then the sequence of structures in the bed should indicate, from bottom

to/

to top, a decrease in flow power of the current. In the majority of field reports where the sequence of internal structures in turbidites has been studied, there is a division of parallel lamination below a division of ripple cross-lamination. This parallel lamination may be of type 1a above, or of type 1b and the logical conclusion is that parallel lamination may form at a higher flow power than current ripple-lamination during deposition of a turbidite bed.

There are, however, two other factors which may play an important part in determining which type of structure forms in a turbidite, viz,

- 1) Rate of deposition - formation of ripples requires slower deposition than formation of parallel lamination.
- 2) Grain size of sediment - parallel lamination forms above current ripple-lamination when the sediment is very fine.

The relationship between parallel lamination and cross-lamination is discussed further, on p. 70.

d) Sequence of internal structures in the graded calcilithites.

It is now accepted that the internal structures of turbidites tend to follow certain sequences from bottom to top of individual beds (Bouma 1962, and FIG. 40; Signiorini 1936; Schaub 1951; Basset and Walton 1960; Dzulynski and Walton 1965; Duff et al., 1967). The 'Bouma' sequence, which is now accepted as the most common model for turbidites, has been interpreted as indicating decreasing flow regime during deposition from a waning current (Harms and Fahnestock 1965; Walker 1965; Walton 1967). The following modifications to

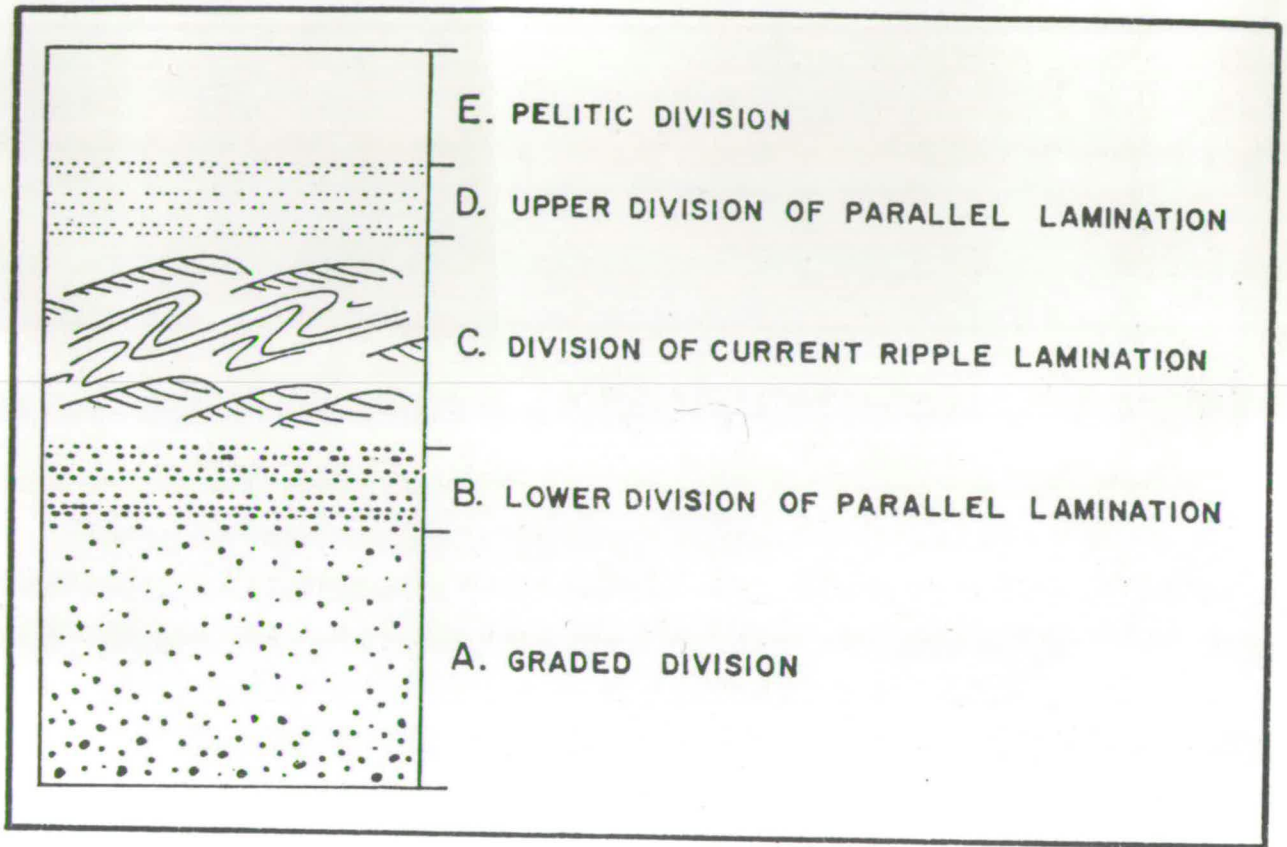


FIG. 40. The 'Bouma' sequence of internal structures in turbidites
(from Walker 1965).

the 'Bouma' sequence have been suggested:-

- a) a lowermost dune division (Hubert 1966)
- b) ripple cross-lamination within the B and D divisions (Hubert 1967).

The sequences of internal structures found in the graded calcilithites of the Lower Breccia flysch facies may be classified as follows:-

- | | | |
|-----------------------------------|---|--|
| 1) 'Bouma' | - | As described by Bouma (1962) with A-B-C-D-E divisions. |
| 2) Interrupted | - | With A and E divisions, and one or more of the other divisions missing. |
| 3) Base cut-out | - | With A, A+B, or A+B+C, missing. |
| 4) Truncated | - | With one or more of the upper divisions missing. |
| 5) Base cut-out
+
Truncated | - | Combination of 3 and 4, i.e. A,E, missing, with or without other middle divisions. |
| 6) 'Duned' | - | Sequence with a dune structure present. |
| 7) Repetitive | - | With two or more divisions of cross-lamination, in each case separated by parallel lamination. |

There is a large variety of sequences in the graded calcilithites, as shown by a section at Praz de Lys (Table III). The 'Bouma' sequence is not common, but sequence 2 is the nearest approach to it. Sequence 3 is considered to have formed by slow deposition of the bottom part of the bed; it is probably found only when the very coarsest part of the current has been removed by deposition nearer to the source. Sequence 4 may result by local deposition of the coarse part and by-passing of the finer part (possibly complementary to the formation of sequence 3), or by erosion of the fine top of a bed by a later current. A combination of factors which produce sequences 3 & 4 could produce sequence 5.

There are two types of sequence in the graded beds of the flysch facies which deserve comment:-

1. A dune structure succeeded by a division of parallel lamination in sand.
2. The alternation, in a single bed, of parallel lamination and ripple cross lamination, with perhaps two or three divisions of each (Plate 30).

Experiments conducted by Simons et al., (1965) have shown that, in the fluviatile case, dunes indicate conditions of higher flow power than do ripples for the same size of bed material. With a model of a decelerating turbidity current, the sequence of structures from bottom to top of the bed will signify the decrease in flow power which accompanies the deceleration (Harms and Fahnestock 1965; Walker 1965; Walton 1967). Observations have shown that the sequence of internal



Plate 30. Deformation in cross-laminated, and in parallel laminated parts of a graded calcilithite. Flysch facies, Lower Breccia, Praz de Lys.

TABLE III. TYPES OF SEQUENCE OF INTERNAL STRUCTURES FOUND IN THE GRADED BEDS.

1. COMPLETE.	A B C D E.
2. INTERRUPTED.	A B C E, A C D E, A C E. A E.
3. BASE CUT OUT.	B C D E, B C E. C D E, D E. Dune C D E, Dune D E, Dune C E, Dune E.
4. TRUNCATED.	A C D, A C, A.
5. BASE CUT OUT + TRUNCATED.	B C D, B C. C D, C. Dune C D, Dune C, Dune.
6. 'DUNED'.	Dune B C D E, Dune B C E.
7. REPETITIVE.	B C B C B C B C D E.

TABLE IV.

Type of Sequence.	1.	2.	3.	4.	5.	6.	7.	TOTAL.
<hr/>								
Thickness (cm).								
<hr/>								
1 - 2			4					4
2 - 4			18					18
4 - 8			4		13			17
8 - 16	1	2	7	1	6	1		18
16 - 32		4	5	1	4			14
32 - 64		1	3		2		1	7
64 - 128		1		1	1	1		4
128 - 256				1				1
<hr/>								
TOTAL.	1	8	41	4	26	2	1	83

=====

structures usually agrees with this. The cases described above must therefore have some other explanation. Cases of a parallel lamination overlying a dune cross lamination have been seen in the Lower Breccia Formation and in the Whitehouse Formation at Girvan, Scotland (Plate 31). If the parallel lamination is believed to have formed in the lower part of the upper flow regime (Harms and Fahnestock; 1965; Walker 1965), while dunes are a stable bed form in the upper part of the lower flow regime, then there is a reversal in the trend of decreasing flow power during the deposition of a turbidite bed. There are three possible explanations. First, there may have been such a great difference in grain size (between the material of the dunes and the material of the parallel lamination), that while the dunes were forming in the pebble and gravel (in the lower flow regime), the material flowing over the top of the dunes was being transported at a flow power compatible with upper flow regime, or even more powerful conditions. Then, as the current decelerated, it became too weak to move the material in the dunes. The next material to be deposited could quite easily be laid down in the upper flow regime where a plane bed was the stable form. Some idea of the scale of grain sizes involved may be obtained from Sundborg's (1956) graph (FIG. 41). The comparison cannot be taken too far because Sundborg was dealing with the fluvial case and velocities 1 m above the bottom. However, consider a velocity of 100 cm per sec - the critical erosion velocity for particles approximately 4 mm in diameter. Now at this

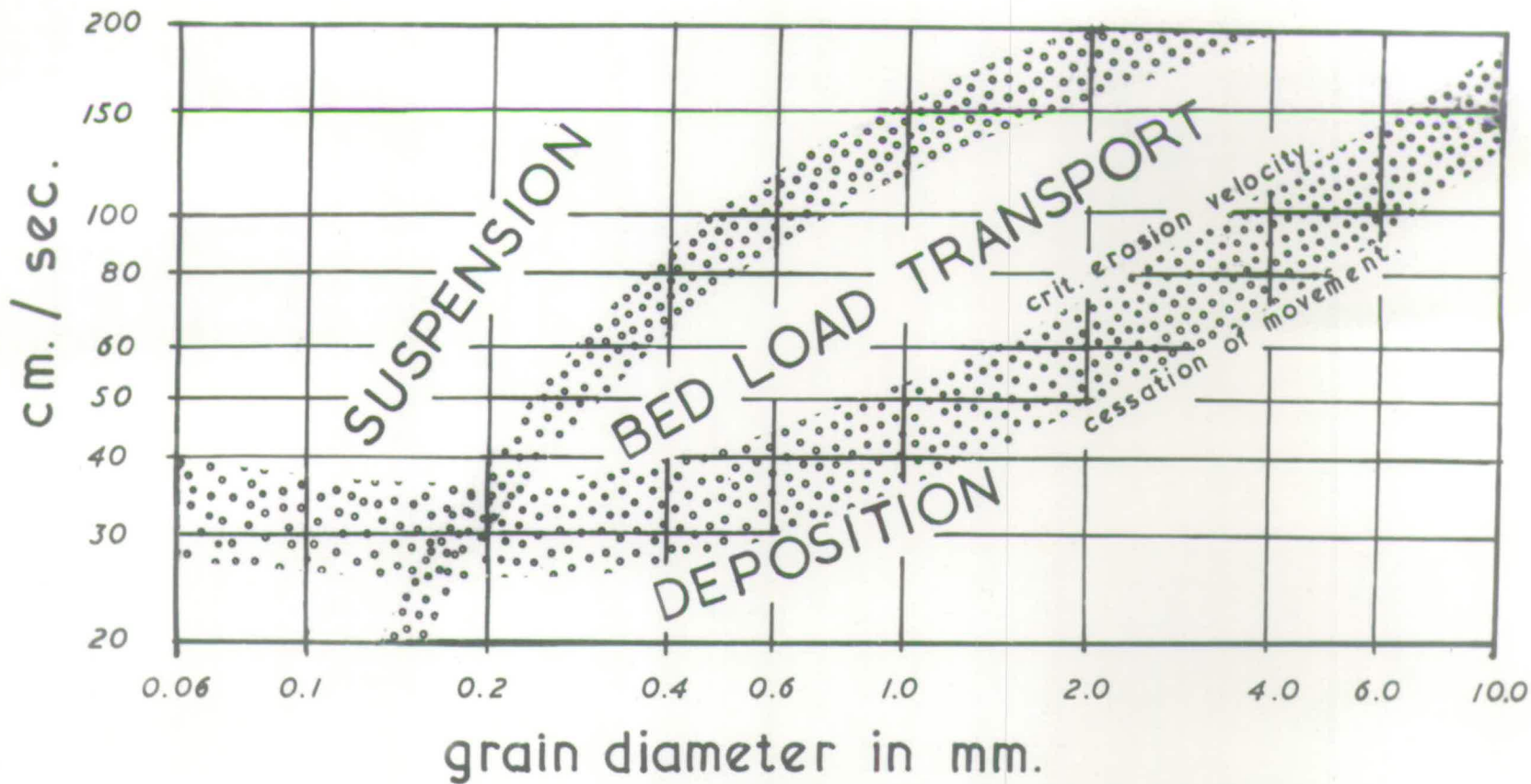


FIG. 41. The relationship between grain size and flow velocity (from Sundborg 1956).

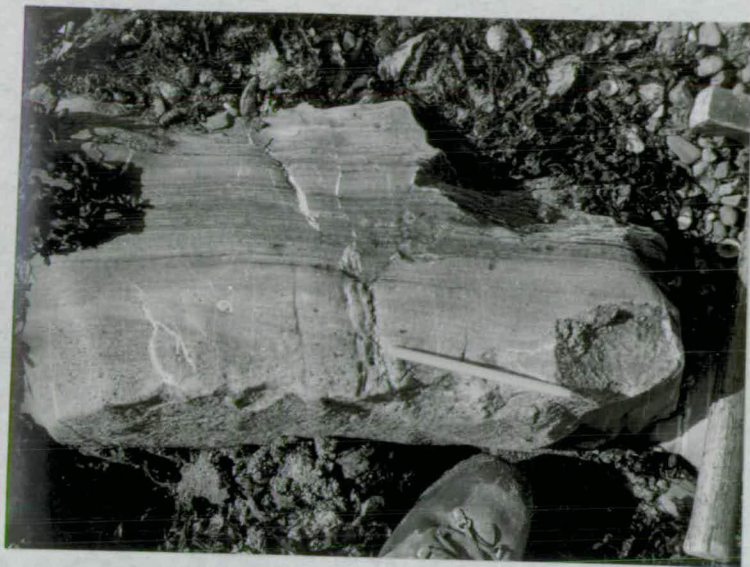


Plate 31. Dune division overlain by parallel lamination in a graded Limestone of the Whitehouse Fmn. (Ord.) at Girvan, Scotland. Pen (13 cm.) is parallel to cross-lamination in dune.

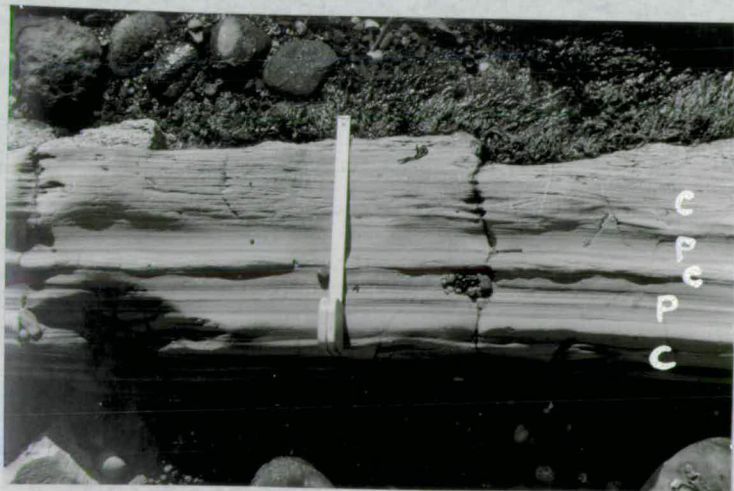


Plate 32. Alternation of cross-lamination (C), and parallel lamination (P), in a graded limestone of the Whitehouse Formation, Girvan, Scotland. Rule is 20 cm. long.

velocity, grains of medium sand, c. 0.5 mm in diameter, would still be carried in suspension, i.e. they would still have the potential of passing through the whole of the upper flow regime during deceleration of the current. This would require good separation of the coarser grains, but the presence of dune structures shows that such separation is possible. The second possibility is that the sequence was formed by two successive currents. However, this would have needed the first current to have deposited only gravel and worked it into dunes, while the second current would have to be free of this gravel, and not to have eroded any of the previously formed dunes. It is therefore considered less likely. The third possibility is that a factor such as rate of deposition may have been most important in the formation of the structures with rapid deposition favouring parallel lamination rather than either dunes or ripples. There is another possibility which cannot be ignored, i.e. that the parallel lamination found above the dunes did not form in the upper flow regime. Allen (1968a - FIG. 3) has produced a diagram based on the data of Guy et al., (1966) which shows that for material of median fall diameter greater than about 0.7 mm there is a range of stream power where a plane bed with movement is stable, and this is in the lower flow regime. This could not have applied in the case of the Lower Breccia example, however, where the material in the parallel laminations is fine enough to occur as ripples.

The second type of sequence, repetition in a single bed, of divisions of current ripple lamination and parallel

lamination, has been reported by Hubert (1967) from the Pre-alpine Flysch of Switzerland, by Gnaccolini (1967) from the Bellunese Flysch of the Appennines, and by Pescatore (1967) from the Miocene turbidites of the Sorrento Peninsula. It appears in the calcilithites of the flysch facies of the Lower Breccia (Plate 30), and in the Whitehouse Formation at Girvan (Plate 32). A straightforward decrease in flow power with decreasing grain size could not produce this. There must be at least some fluctuation, either in the flow power during deposition, or in the size of material being deposited at a particular time. This could be achieved because of eddies within the current having different velocities, or because there were pockets of coarser material in the current. A more detailed study of the example shown in Plate 30 suggests that variation in flow power within the current, rather than variation in the grain size being deposited, is the principal factor in production of this type of sequence. The sequence of structures in the bed is as follows (FIG. 42):-

10. Pelite. (L).
9. Parallel lamination in silt and pelite. (K).
8. Ripple cross lamination in silt/sand. (J).
7. Parallel lamination in silt/sand. (I).
6. Ripple cross lamination in sand/silt. (F),
passing laterally to parallel lamination in sand/silt. (H).
5. Parallel lamination in sand. (E).
4. Ripple cross lamination (deformed) in sand. (D).
3. Parallel lamination in sand. (C).
2. Ripple cross lamination in sand. (B).

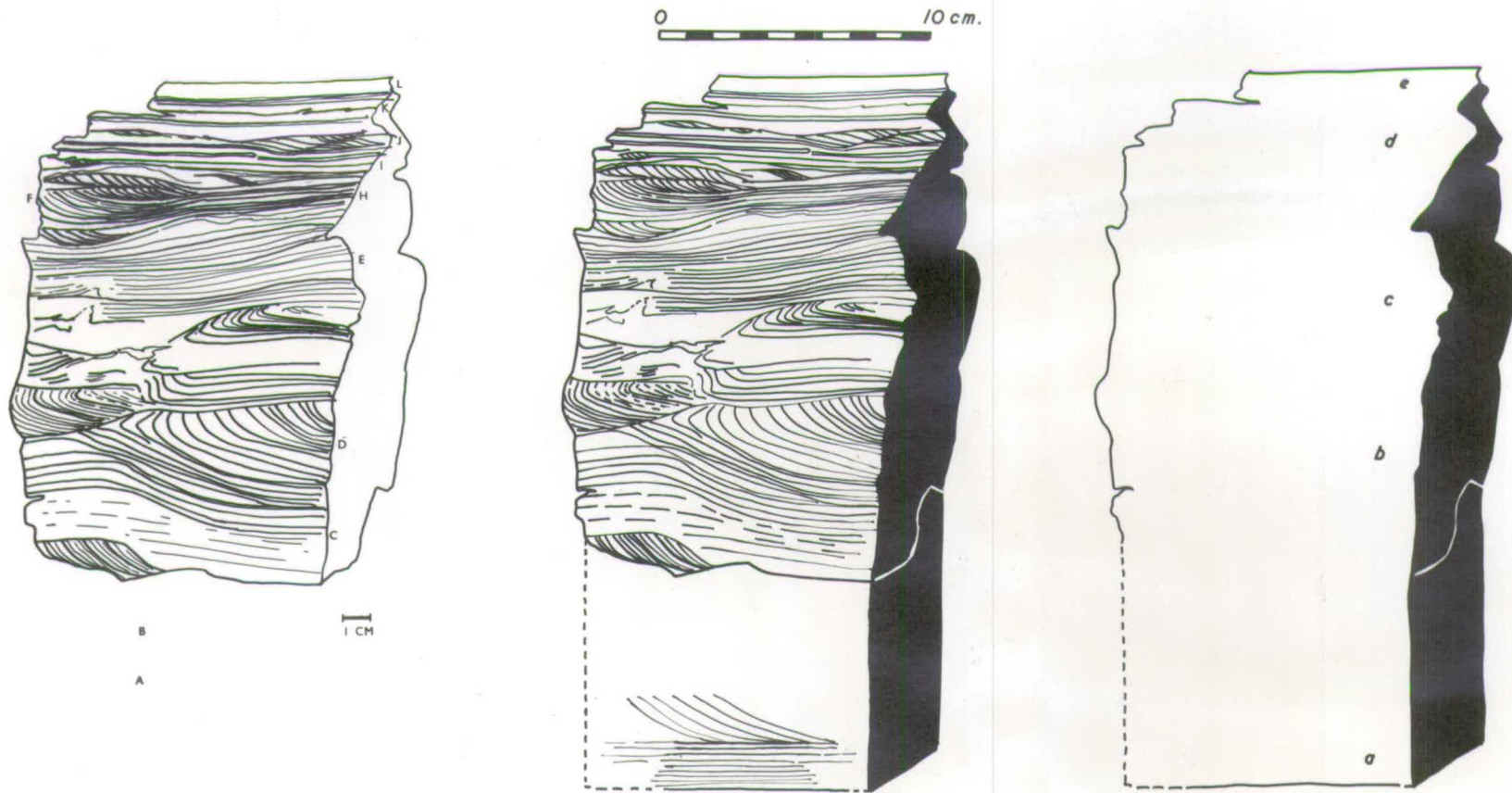


FIG. 42. Repetitive sequence of internal structures (centre), showing structures referred to in text (left), and positions of grain size analyses (right).

1. Parallel lamination in sand. (A).

The portions of the bed marked K and L are considered to represent the D and E divisions of Bouma (1962). There are thus four sets of a presumed B division of parallel lamination, overlain in each case by a C division of current ripple lamination. Grain size analyses of specimens from the parts of the bed marked a, b, c, d, and e, (FIG. 43) show that the bed is graded throughout these repetitions of the B and C divisions (FIG. 42). This means that during deposition of the bed, grain size was constantly decreasing. Reference to the figure published by Simons et al., (1965) (FIG. 35) shows that if grain size was decreasing, then to produce alternations of parallel lamination and ripple cross lamination would need variations in flow power within the current.

In the fluvial case flow power can vary across the width of the river with upper flow regime and lower flow regime conditions prevailing at the same time on different parts of the river bed. A similar situation could presumably exist in the case of a turbidity current.

There is the alternative that the repetitions may have been produced as a result of fluctuations in the rate of deposition from the current. If rate of deposition from the current was greater than the rate of build-up of current ripples then parallel lamination would be favoured.

From the examples discussed above, it seems that the model of deposition from a turbidity current is somewhat more complex than has been suggested by Harms and Fahnestock (1965), Walker (1965), and Walton (1967), with factors such as rate of

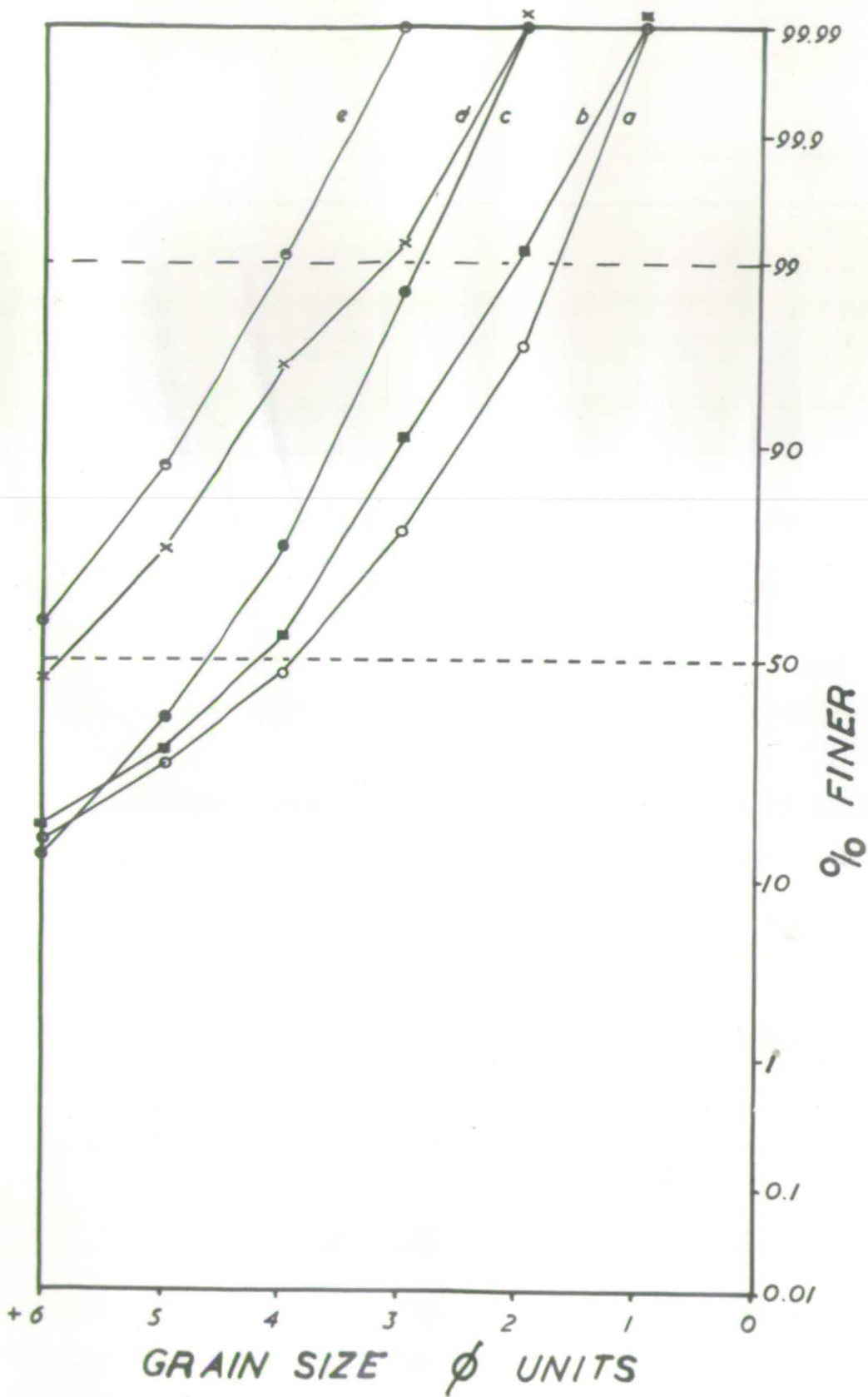


FIG. 43. Cumulative frequency/grain size curves for repetitive sequence (shown in FIG. 42).

The data are uncorrected and derived from point count analyses.

deposition (Walton 1967), and grain size distribution playing an important part.

e) Grain lineations in sand grade beds.

Inspection of many thin sections has revealed that a high degree of preferred orientation of grains is uncommon in the calcilithites. It seems likely that a degree of preferred orientation would be more easily formed in those beds with deposition slow enough to allow a period of traction before the particles finally come to rest. Such beds would be also more likely to have internal laminations. Two beds, one with internal laminations (Plate 33), and one without, but with good continuous grading (Plate 23), were analysed for preferred orientation of long axes of grains. As expected, the bed with good lamination shows a preferred orientation (FIG. 44, e,f,g,h,i), while that with grading only, has no preferred orientation (FIG. 44, a,b,c,d). The preferred orientation in the first bed is approximately normal to the current direction deduced from the ripple cross lamination in the bed. A preferred orientation normal to the current direction was reported by Parkash and Middleton (1969) in one case from the turbidites of the Gaspe-Peninsula, Quebec.

It is suggested that a preferred orientation of grains, and internal parallel and cross lamination is developed as a result of slow deposition from the current, which depends on rate of deceleration of the current. Parallel lamination will require less time than will ripple cross lamination. In the

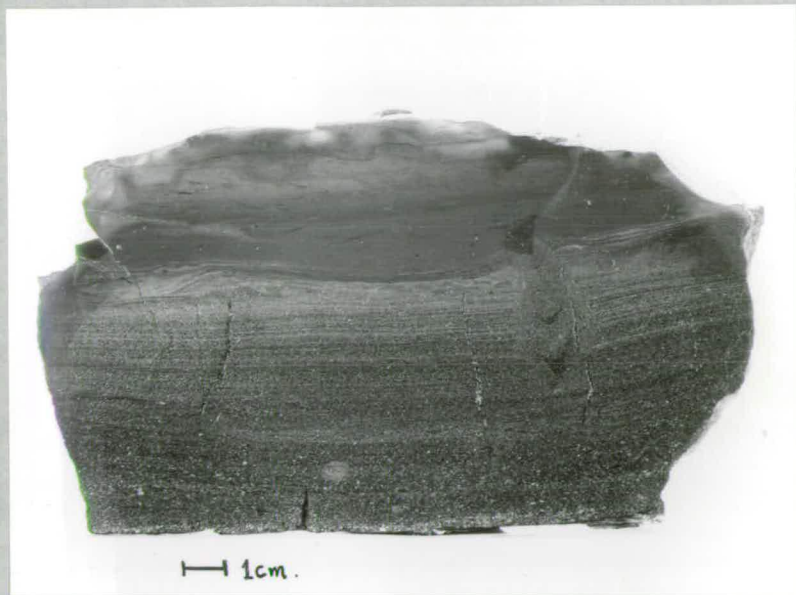


Plate 33. Graded, parallel laminated calcilithite which was analysed for preferred orientation of elongate grains.



Plate 34. Convolute parallel laminae at top of graded calcilithite. Flysch facies, Lower Breccia, Praz de Lys. Scale in cm.

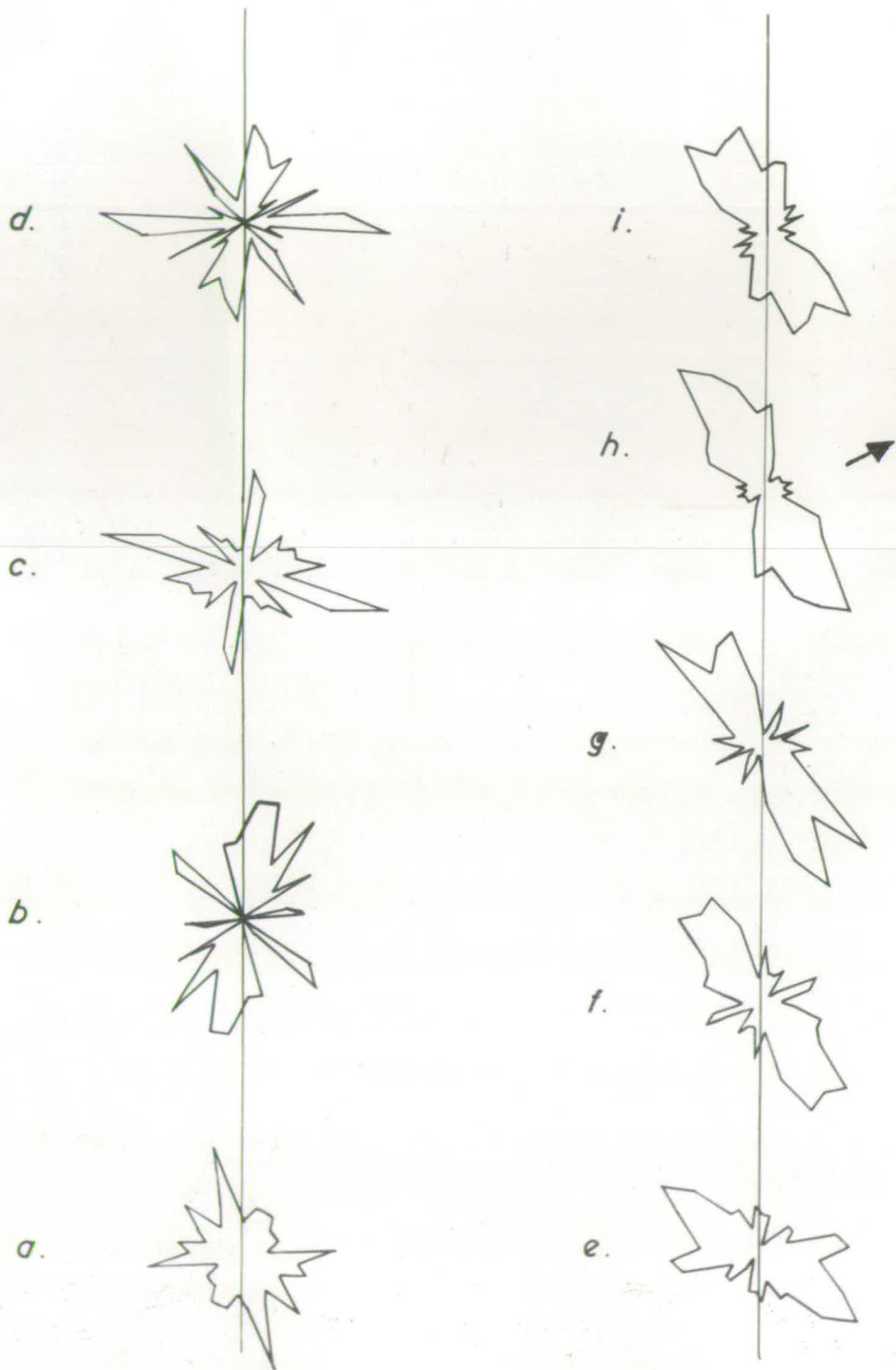


FIG. 44. Grain orientation in two graded calcilithites. a - d continuously graded calcilithite without structures. e - i graded calcilithite with structures. Flysch facies Lower Breccia.

In the left hand figure the vertical is an arbitrary direction. In the right hand figure north is to the top, and the current direction from ripple marks is shown by the arrow.

bed shown in Plate 33 the parallel lamination is considered to have formed by the 'like seeks like' mechanism (Kuenen 1966a). In this way, the parallel lamination has formed by the accumulation of layers which may be only one grain thick, and differing in size, shape, or mineralogy. This can occur with little or no intermittent transport of the individual grains. In contrast, the formation of ripple cross lamination requires intermittent transport of grains up stoss slopes and down lee slopes (Allen 1968b). Thus rate of deposition can decide presence or absence of a C division. Similarly, rapid deceleration of a current will reduce transport and again, if lamination forms at all, it is more likely to be parallel lamination.

f) Convolute and deformed lamination.

Convolute lamination is fairly common in the calcilithites, in either cross-lamination or parallel lamination (Plate 34). It usually occurs in the fine sand/silt-grade parts of a bed. It is rarely seen in plan, but when it is, it is limited in lateral extent and forms a nodose surface. In beds with dune structures, the sand filling the dune troughs is often convoluted. Exposures were not suitable for measurement of orientation of the axial planes or fold axes of convolutions.

Deformation of laminations in coarser material also occurs (Plate 30). Overturning of the cross laminae in a down-current direction, as deduced from cross-lamination elsewhere in the bed, may indicate production of the deformation by current

drag at the upper surface (McKee, Reynolds & Baker 1962; Rust 1968). Further proof that deformation has taken place during deposition of the bed is given by the lack of deformation of the laminae at the top of the bed. Also, the deformation just below X must have taken place before deposition of the cross-laminations at X.

3. The calcilithite/pelite lithology.

This is the third type of lithology found in the flysch facies. It is characterized by the alternation of thin sand-silt grade beds with interbeds of calcareous silty pelite. The sand-grade beds usually grade into the pelites, sometimes rather rapidly. In the measurement of field sections, an arbitrary upper thickness limit of 5 cm was set for the sand grade beds of this type, but in practice they vary greatly in thickness laterally, sometimes from 1 cm to 10 cm in a few metres. At Praz de Lys, thickness variations in three successive sand beds are considerable over an outcrop length of 11 metres (FIG. 45). The thickness variations in these thin sand beds are compensated for by variations in thickness of the interbedded pelites, rather than by variations in successive sand grade beds, as shown by the plot of cumulative thickness of the three sand beds against outcrop length. Thus these 'units' are of limited lateral extent and are possible lateral equivalents of, rather than vertical alternatives to, slightly thicker graded calcilithites. Tracing these beds along the strike showed that maximum thickness was about 10 cm, there is no evidence to suggest that they pass into beds any thicker than this. The sandy parts in

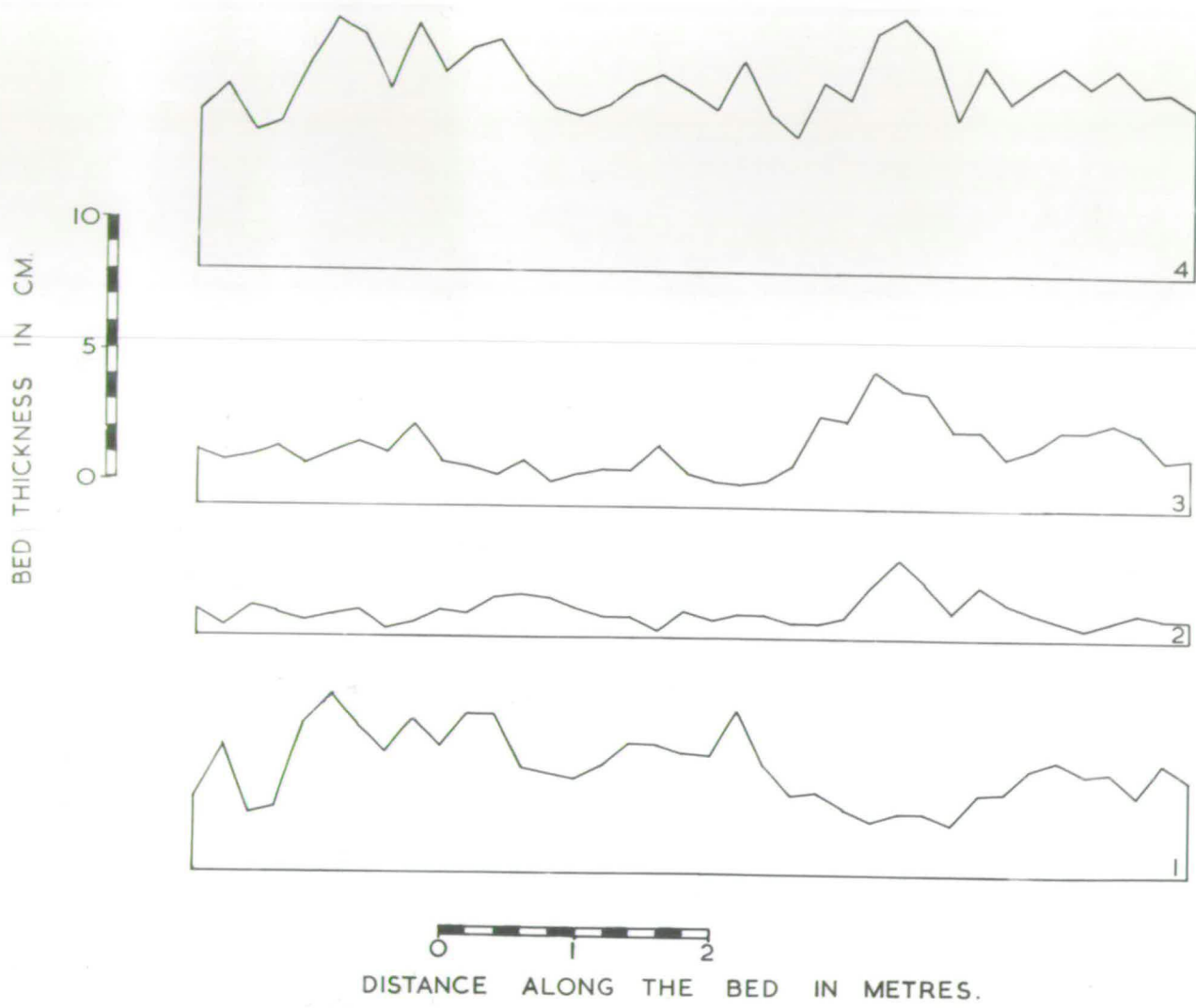


FIG. 45. Lateral thickness variations in the calcilithite units of the calcilithite/pelite lithology, flysch facies, Lower Breccia. 1, 2, and 3, are for single calcilithites, and 4 shows the cumulative values for 1, 2, and 3.

these thinner beds are often rippled or have parallel laminations, but at Praz de Lys the development of internal structures in such thin beds is limited and generally rather poor. However, at Avoreaz, thin beds like this with well-developed internal structures are found (Plate 35). When the beds are thin like this, lensing-out of either the sand part, or of the pelitic part may occur.

The grading and internal structures suggest deposition from small-scale turbidity currents. The discontinuous nature and variable thickness of the beds could be a result of rapid deposition of silty/sandy material from predominantly muddy currents.

4. Factors affecting bed configuration in the breccias and calcilithites of the flysch facies.

The mode of transport and deposition, and therefore the resulting nature of a breccia or calcilithite bed depends on three factors:-

1. The original proportions of sand and gravel material.
2. The relative velocities of the sand and gravel portions.
3. The rate of deposition.

The possible combinations of these three factors and the types of bed which they produce are shown in FIG. 46. On the left are hypothetical velocity-height curves for the inertia-flow and the turbidity-flow parts of a complete flow. On the right, in column (A) are shown the resulting bed configurations where there is a large proportion of coarse material. On the extreme right, in column (B) is shown the bed configuration which results when

coarse material forms only a small proportion of the total flow.

First of all, the proportion of coarse material is the major factor in deciding whether or not an inertia flow forms. If there is but little coarse material, then the flow is essentially a turbidity flow which may or may not have a traction carpet of coarser grains, and the resulting bed would be a calcilithite.

If there is a large proportion of gravel grade and coarser material, it is unlikely that it could all be entrained by the turbidity current, and it would therefore travel as an inertia flow, while the sandy and muddy part would form a turbidity flow above.

If the turbidity flow had a higher velocity than the inertia flow (FIG. 46-1) traction structures might form at the top of the inertia flow. This would be likely to occur during the depositional phase of the inertia flow if any structures were to be preserved. Also, deposition of overlying material (from the turbidity flow) would have to take place while the structures were still hydrodynamically stable. Gravel waves could form in this way (FIG. 46-1-(A)). A similar bed could result if a turbidity current flowed over a previously deposited gravel bed. In either case, it would be likely that the turbidity current had sufficient power for most of it to by-pass the site where the gravel waves had formed.

If the turbidity flow had a lower velocity than the inertia flow (FIG. 46-2), all of the gravel would be carried in

the inertia flow. The turbidity flow would have little or no effect on the upper surface of the gravel since there would be a negative velocity gradient at the top of the inertia flow. The resulting bed might be similar to that in FIG. 46-2-(A), with a structureless contact between the coarse and fine parts of the bed.

If the turbidity flow and the inertia flow had approximately the same velocity (FIG. 46-3), deposition could be more or less continuous, and with some mixing at the boundary of the coarse and fine material a bed configuration like that in FIG. 46-3-A could result.

If the coarse material formed only a small part of the whole flow then the possibility of an inertia flow would be unlikely. What would be more likely is that the gravel material would travel as a traction carpet, or that it would be entrained by the turbidity flow. In these cases, the rate of deposition would play an important part (Walton 1967). With slow deposition (FIG. 46(B) 1 & 2) separation is good and a distinct size break occurs - there may or may not be traction structures in the gravel at this break. With fast deposition, separation is limited and large clasts may be frozen in position well above the base of the bed (FIG. 46(B) 3).

All the bed configurations shown in (B) could result farther out in the basin than the bed configurations in (A) if the conditions in 1 (FIG. 46) applied, and a turbidity flow carried off some of the gravel from the top of a previously deposited gravel bed.

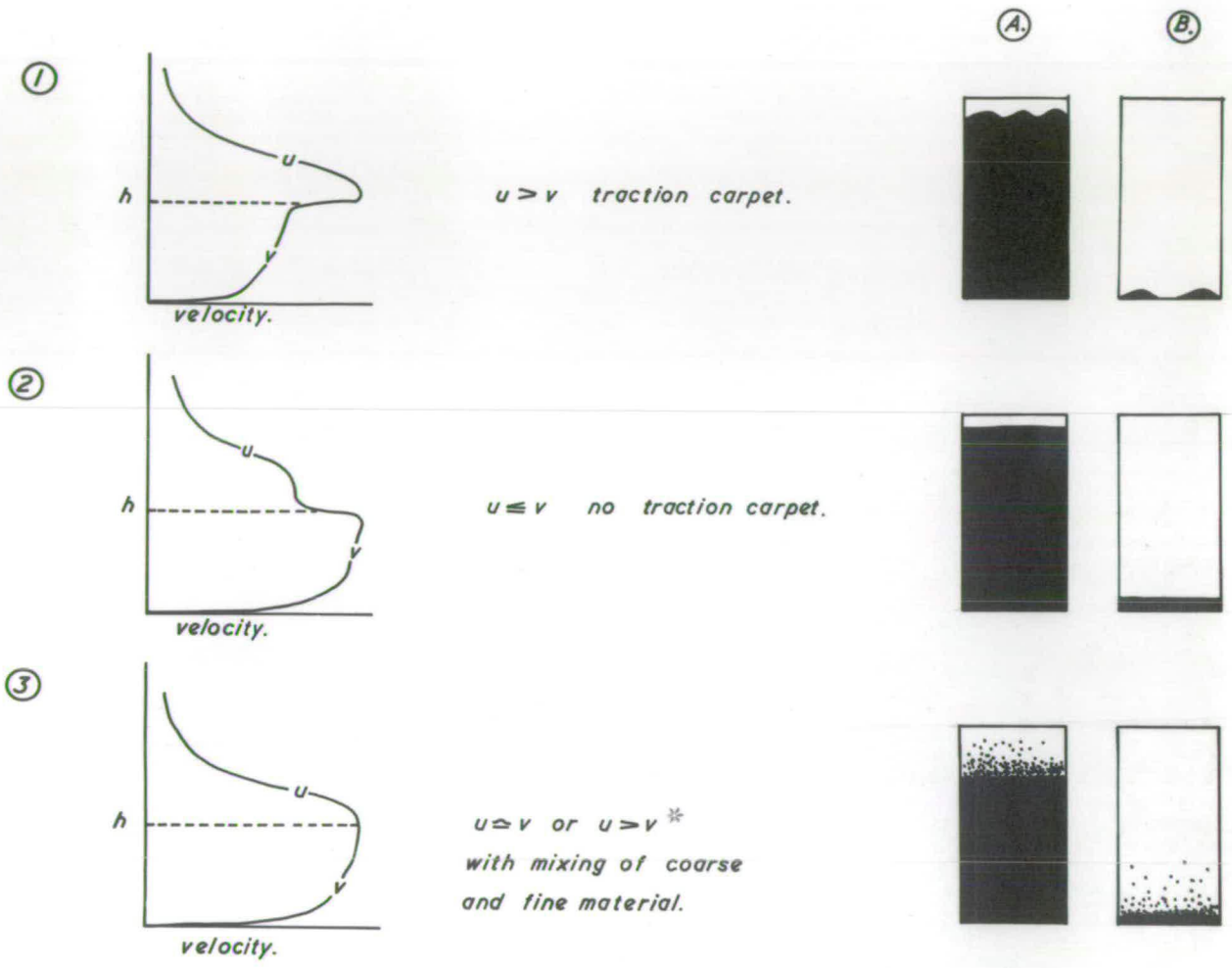


FIG. 46. Presumed mode of formation of different types of bed in the flysch facies, Lower Breccia. * this refers to conditions in 1 when deposition is rapid, and separation of coarse and fine is poor.

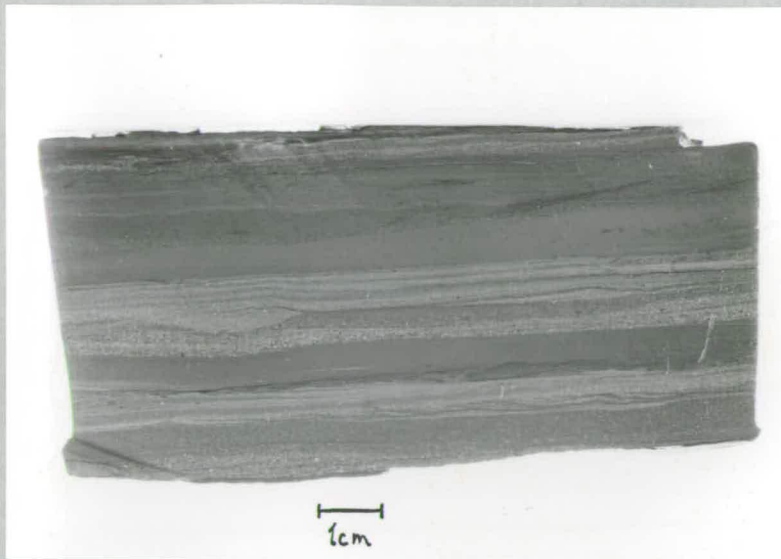


Plate 35. Thin beds of the calcilithite/pelite lithology with grading, and internal structures. Flysch facies, Lower Breccia, Avoreaz.

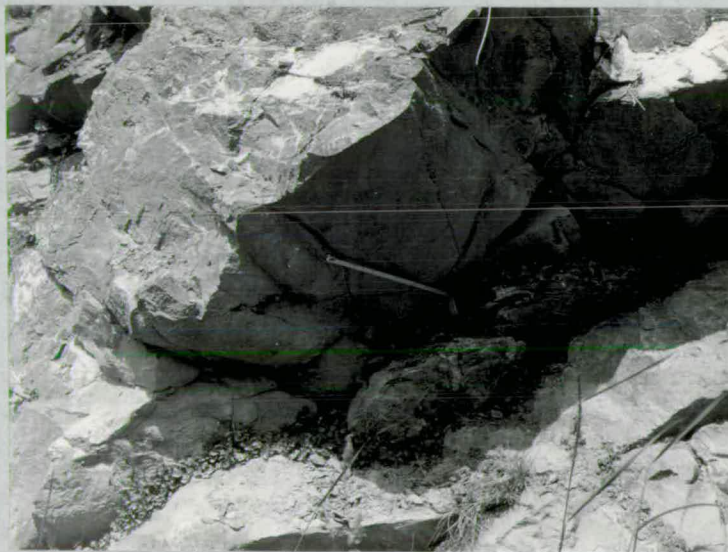


Plate 36. Poorly developed flute markings on calcilithite sole. Flysch facies, Lower Breccia, Les Lindarets.

5) Palaeocurrent analysis.

Palaeocurrent indicators in the flysch facies of the Lower Breccia are scarce but the following have been used:-

1. Sole markings.
2. Gravel dunes and wave forms.
3. Ripple marks and ripple cross-lamination.

The sole markings usually occur as poorly developed flute moulds (Plate 36). There are not many examples, but measurements from widely separated localities (FIG. 47) show a reasonably consistent direction, indicating a north-west, west-north-west, west, or south-west source. In most of the cases current sense cannot be determined, but none indicate an easterly source. The directions indicated by these sole markings are compatible with derivation of the rocks from the west-north-west as suggested by the main direction of thinning of the flysch facies.

Orientation of dune and gravel wave crests are predominantly north-west to south-east (FIG. 48) and where there is internal cross-stratification it indicates a south-west origin. The directions deduced from dune forms at Praz de Lys are fairly constant but at variance with the few sole markings at the same locality.

Orientation of the ripple crests in the calcilithites of the flysch facies show as a wide spread (FIG. 49). Where possible, the sense of dip of the cross-laminae has been indicated (FIG. 49, inner circles). These readings were

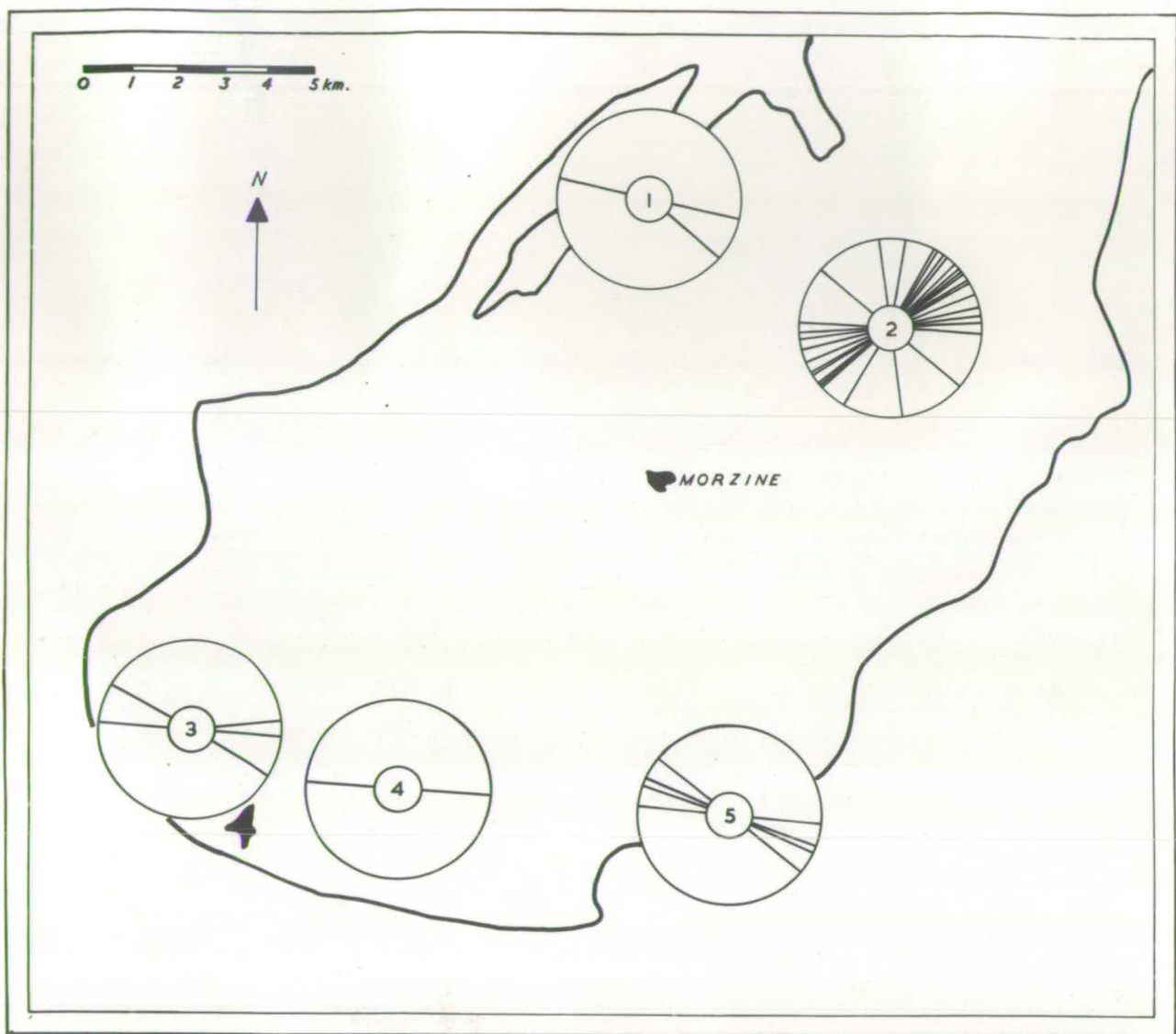
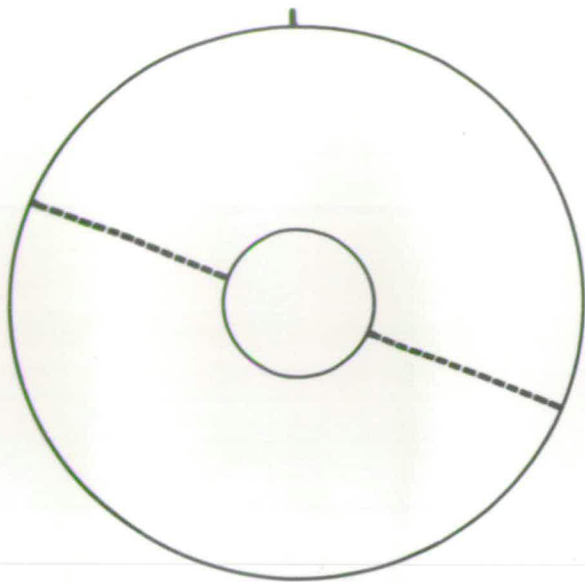
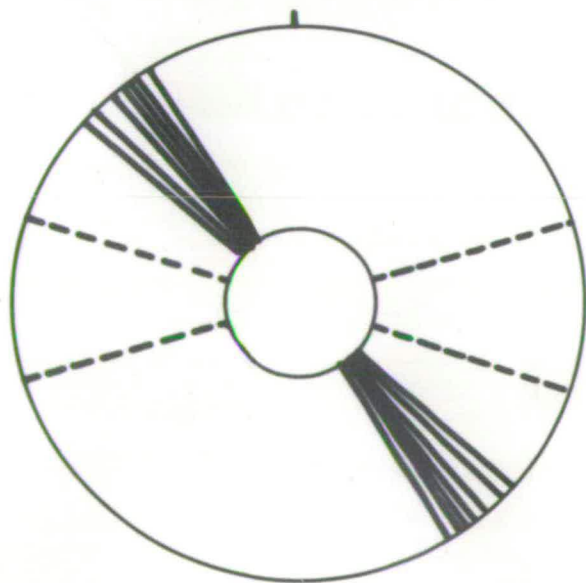


FIG. 47. Palaeocurrent directions deduced from sole markings, flysch facies, Lower Breccia.



Roc de Tavaneuse



Pic de Marcelly

FIG. 48. Orientation of dune crests (solid), and gravel wave crests (dotted) in the calc lithites of the flysch facies, Lower Breccia.

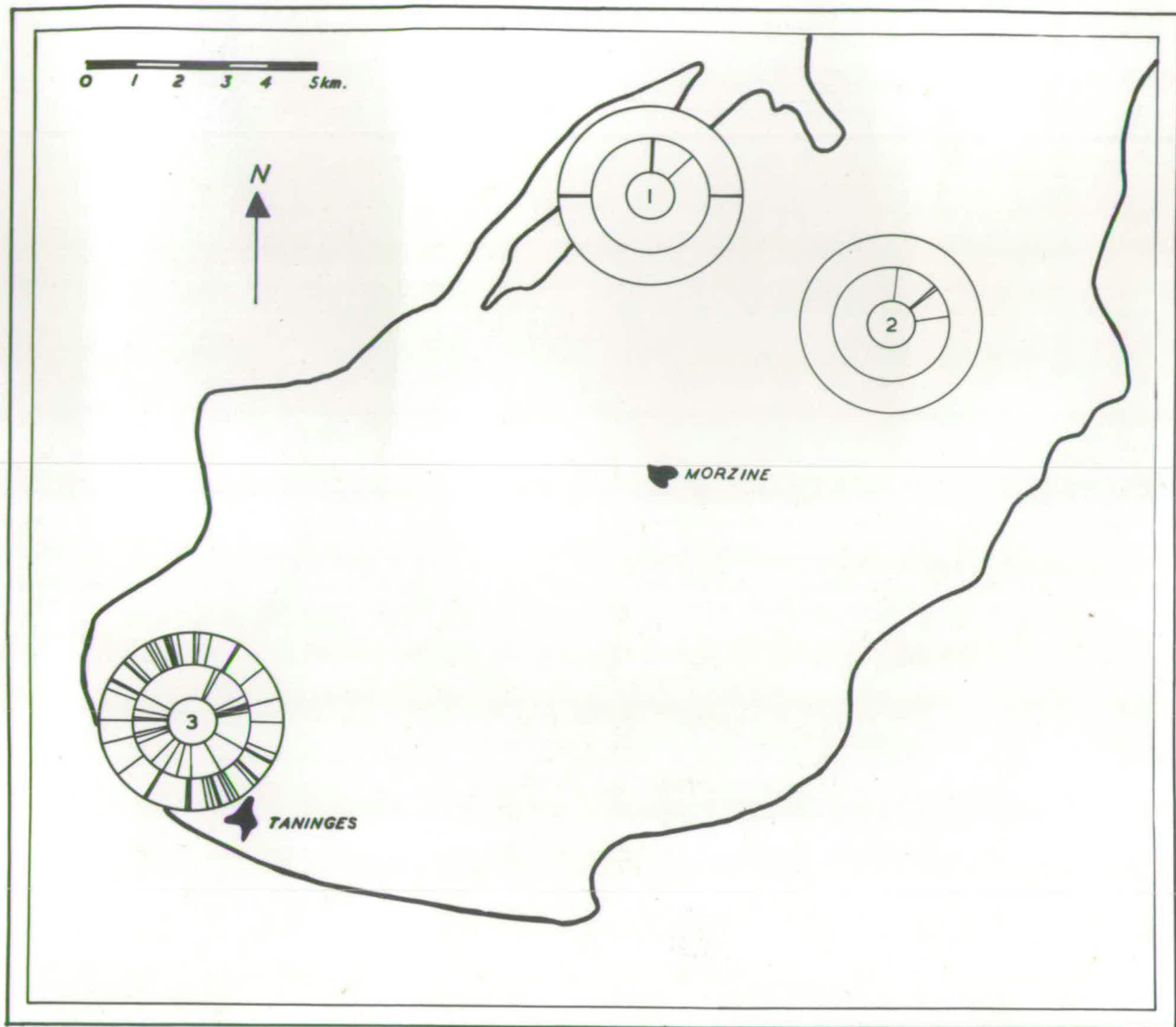


FIG. 49. Orientation of ripple crests (outer circles), and dip of cross laminations (inner circles), in calcilithites of the flysch facies, Lower Breccia.

obtained from the C divisions in the thicker graded calcilithites, and in the thin sand-grade units of the calcilithite/pelite lithology. As well as a wide general variation, the ripple marks show considerable variation over short stratigraphic sections. A section 10 m thick at Praz de Lys shows considerable changes in current direction as deduced from the direction of dip of the cross-lamination only a few beds apart (FIG. 50).

It would be expected that palaeocurrent directions from sole markings and dunes would be similar, since flutes are formed at high flow power (Allen 1968c) and for a turbidity current to form dune structures in gravel its flow power would have to be high. The main difference between the two structures is that flutes are erosional while dunes are depositional. It may be that whereas a flute could form across a slope, dunes would form with their cross-stratification dipping downslope. If in its early stages a turbidity current could flow across a slope, by virtue of its proximity to source and consequent initial high momentum, the divergence of the two structures may be explained.

In contrast to the flutes and dunes discussed above, ripple marks are formed at relatively low flow powers (lower flow regime of Simons et al., 1965). At low flow powers a turbidity current is much more likely to have its flow direction modified by irregularities in bottom topography, especially if it is a thin current. The greatest degree of variation in current ripple orientation is found in the beds of the calcilithite/pelite lithology (FIG. 50). However, this is still not sufficient to

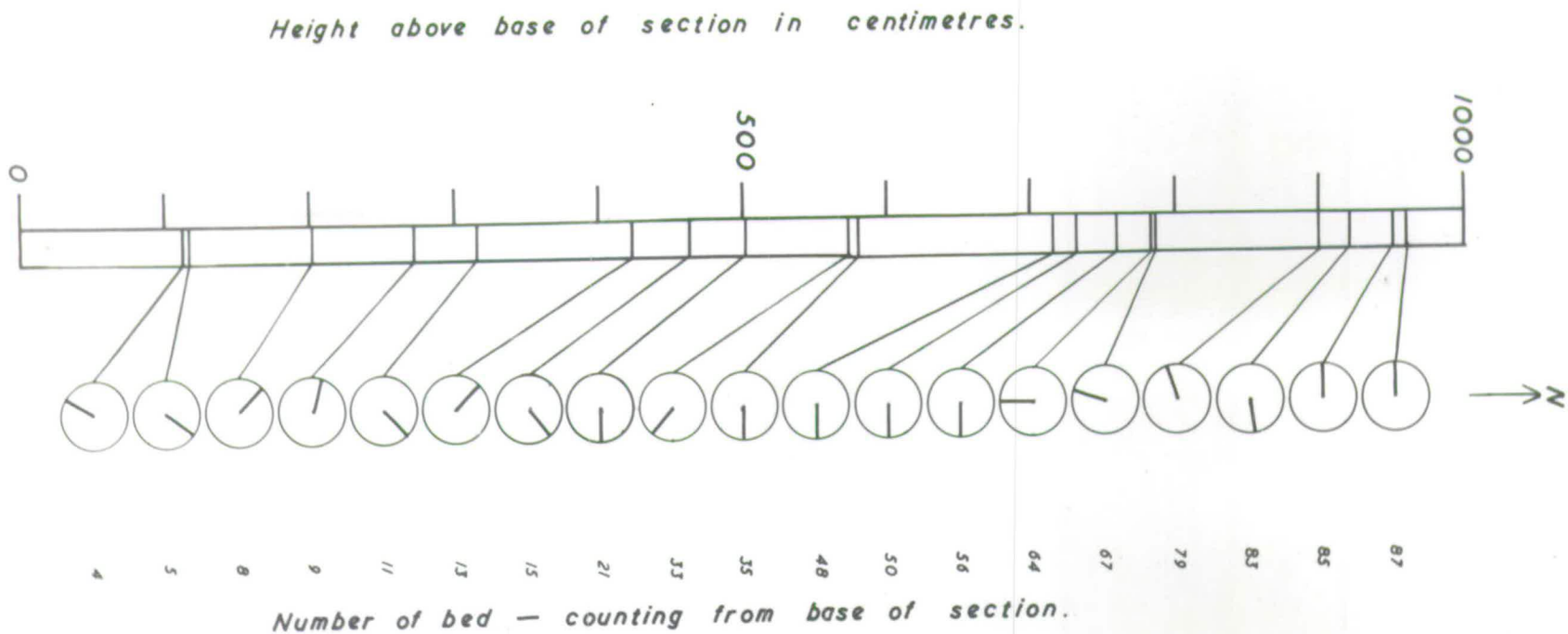


FIG. 50. Current directions deduced from ripple marks in successive calcilithite beds of a calcilithite/pelite unit, flysch facies, Lower Breccia.

explain directions which are counter to the normal trend at this locality. This must be a result of either bottom current redistribution of the material, or the fact that the thinner beds, which occur in the calcilithite/pelite lithology, were deposited from turbidity currents which originated to the north or even north-east of the site of deposition. The lack of evidence for deposition of thicker calcilithites by currents flowing from the north-east makes the latter suggestion unlikely. The grading, and the large proportion of pelitic material makes the former seem just as unlikely, but in view of the orientation of the ripple marks, some influence by sparse intermittent bottom currents cannot be dismissed.

6) Dispersal of the flysch facies.

Thickness variations, and palaeocurrent directions from sole markings, and dune structures, favour a more or less west to east dispersal of the flysch facies, while the variability in direction indicated by the ripple cross-lamination suggests that some reworking by bottom currents may have been involved. The bulk of the evidence does not favour deposition by indigenous bottom currents. The breccias have sedimentary structures indicative of deposition from inertia flow (Sanders 1965), and the calcilithites, of turbidity flows. They are all, without exception, graded in whole or in part. The dunes and gravel in the coarser material have formed in single sets only. Negative evidence for the lack of bottom currents includes the absence of thick sequences of structured, ungraded, sand and gravel, the absence of sand-filled channels or washouts, and the absence of traction structures in the thick coarse breccia beds. The

breccias have not been introduced by indigenous bottom currents, and the evidence favours an inertia flow origin - it would have been surprising indeed if the disturbances associated with flow of large amounts of boulders had not caused formation of turbidity currents of finer material. The features of the calcilithites confirm that this was the case.

The pattern of dispersal of the flysch facies does not seem to have involved much derivation of material from the Roc de Tavaneuse region, which was a centre of thick breccia accumulation during the earlier part of Lower Breccia times. In fact, the sole marking orientations at Les Lindarets suggest a west/south-west derivation, and directions radiating from Roc de Tavaneuse do not occur. In a similar fashion, the directions obtained from the south-west of the area do not radiate from Pic de Marcelly. It seems, therefore, that with the change from the breccia facies to the flysch facies, there was also a change to a more uniform sediment dispersal pattern.

7) Environment of deposition of the Lower Breccia.

Deposition of the Lower Breccia began with supply of very coarse material, often of boulder grade, from a source believed to lie to the north and west of the site of deposition. The essentially fan shaped wedges of this coarse material - known as the breccia facies - are believed to be the result of the building up of submarine fans. There were at least two fans, one radiating from the region of Pic de Marcelly, and another

spreading out from the north of the present nappe near Roc de Tavaneuse - there may have been a third in the area to the northeast, mapped by Chessex (1959). The lack of a muddy matrix in the breccias, the very coarse clasts, and the lack of structures except in the finer grained parts is considered to indicate that most of the breccias were transported by a process of inertia flow (Sanders 1965). Deposition of the finer sediment was not common in the breccia facies. Cross bedding at the tops of breccias in material of pebble and finer grades, and one case of parallel laminated sand lens in the main part of a breccia, indicate the operation of bottom currents.

After deposition of the breccia facies, operation of strong bottom currents halted. No traction structures were formed in gravel except dunes which appear at the bases of some turbidites and these are believed to form purely as a result of movement of gravel by turbidity currents. Beds tended to be fairly thin, considering the coarse nature of the material. The beds show considerable variety in the relative types and abundance of sedimentary structures produced. Bed thicknesses are often variable over short distances. Beds of boulder grade may alternate with beds of silt grade. Inertia flow, in the case of the very coarse beds, and turbidity flow, in the case of the finer beds were the main means of transport. Erosive power of such flows was very small and channeling and scouring are uncommon. Periods of deposition of thick coarse breccias alternated with periods of deposition of thinner, finer, graded beds, but conditions of turbidity current deposition predominated

throughout. Only in the ripple marking of the calcilithite/pelite lithology, does extreme variability in palaeocurrent direction suggest that there may have been some modification of structures by bottom currents, though these must have been sporadic. The source area for the flysch facies material, which is similar to the material in the breccia facies, was to the west and north-west.

Towards the south-east of the nappe, the flysch facies of the Lower Breccia is believed to pass into the Lower Shales Formation with decrease in number and thickness of both breccia and sand-grade calcilithite beds.

III. THE UPPER SHALES FORMATION.

The Upper Shales lie between the Lower and Upper Breccia Formations. In spite of the French name of Schistes Ardoisiers - literally "slaty shales" - the formation is not at all slaty in the area of the present study, and deformation has been restricted to the development of a rather poor fracture cleavage in the mudstones.

With a large proportion of fine-grained beds, and frequent siliceous beds, the formation forms a marked contrast to the coarse carbonate sequences above and below. The formation varies in thickness from 300 m to zero (FIG. 51). There is a gradual passage down into the Lower Breccia, while the transition to the Upper Breccia is more rapid.

Apart from the much finer-grained nature of the Upper Shales, lithologies are different from those found in the breccia formations. All of the rock types in the Lower Breccia occur also in the Upper Shales but the breccias and calcilithites tend to be thinner and less abundant. Calcareous and dolomitic shales occur but they form beds up to several metres thick. The most distinctive members of the Upper Shales are siliceous red and green mudstones. There are also thin graded sandy siltstone beds. When compared with the Lower Breccia, the main differences are the introduction of more siliceous material, and the reduction in quantity and grain-size of the carbonate material.

1. The breccias in the Upper Shales.

These form only a small proportion (12%) of the total thickness measured in the Upper Shales. They are

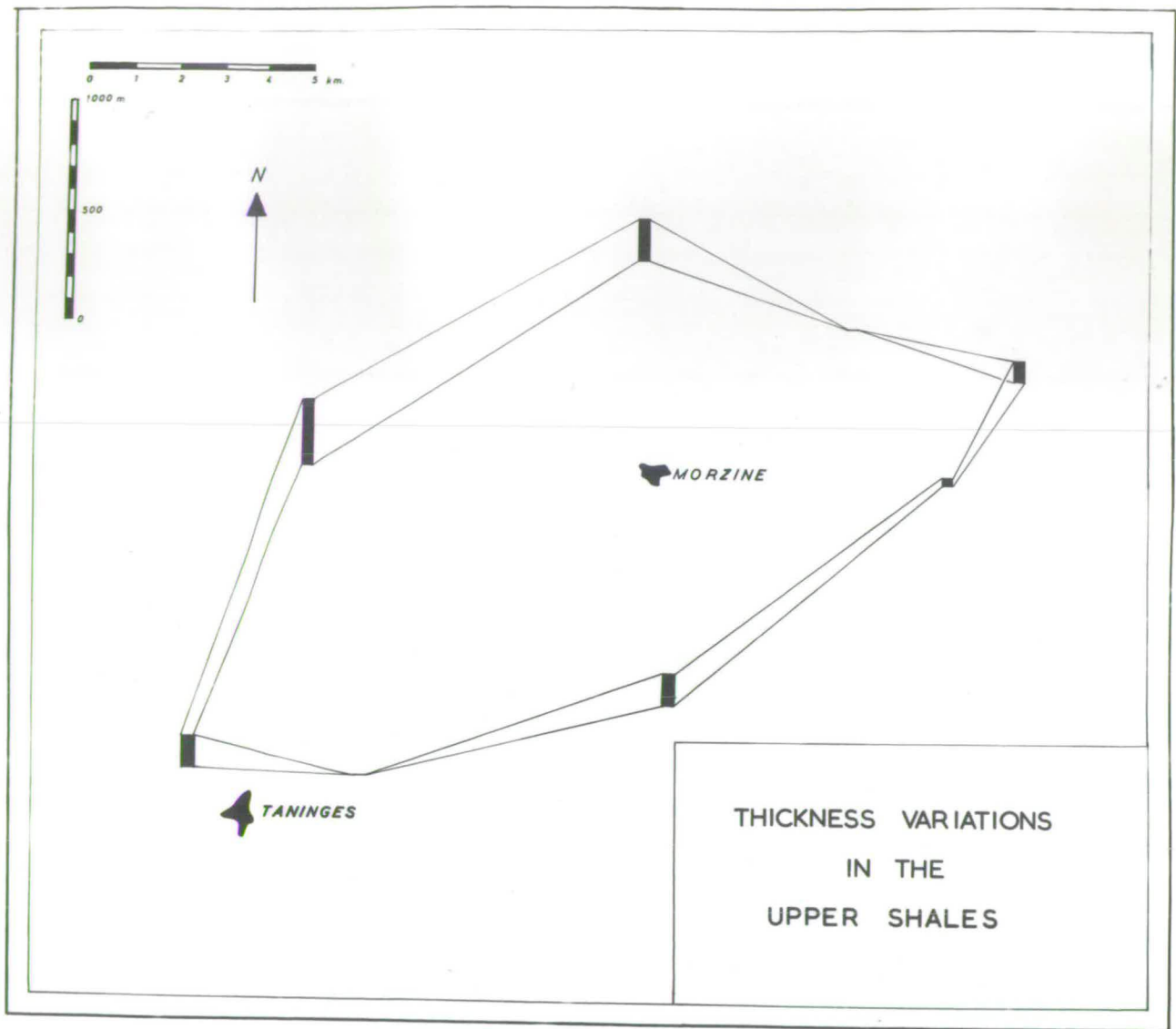


FIG. 51. Geographic variations in thickness of the Upper Shales.

generally thinner than those of the Lower Breccia, varying in thickness from 4 cm to 500 cm with a modal value of 8 - 16 cm (FIG. 52), but they are of the same textural type i.e. there is a closed framework of clasts with no fine matrix, although there may be interstitial sand-grade material. The thicker and coarser beds are similar to those found in the flysch facies of the Lower Breccia with fining towards the tops, and the thinner ones are well graded (Plate 37) and generally less than about 30 cm thick. The breccias are not confined to any one part of the formation but the only case of thick breccias is at the very top of the Upper Shales at Praz de Lys. The thinner breccias have a distinctive rust weathering colour, a consequence of the ferroan dolomite cement.

2. Calclithites.

These form about 5% of the measured thickness. They are generally thin, usually about 5 cm thick (FIG. 52). They all show some grading, from sand or silt, rarely gravel, to clayey pelite. They seldom have ripple marking but parallel lamination of the sandy parts is common.

3. Shales and mudstones.

These occur as thick beds, up to 1000 cm, (FIG. 52, Plate 38), of black and grey calcareous shales, yellow dolomitic shales, and red and green mudstones. The red and green mudstones are more common in the upper part of the formation. They are compact and hard, unlaminated, and have yielded no fossils. By contrast, the shales lower in the formation are fissile, and crumbly with

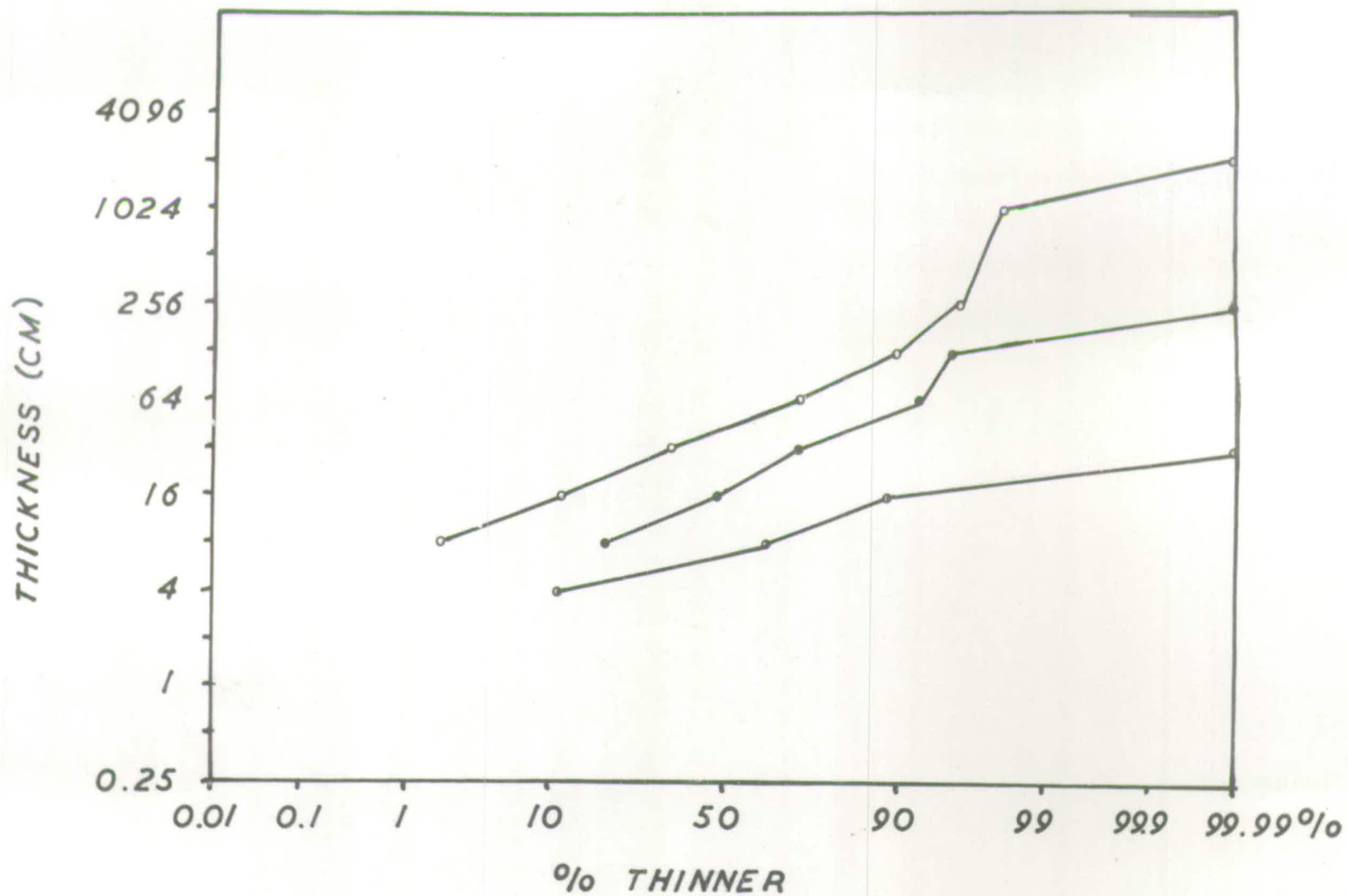


FIG. 52. Cumulative frequency/bed thickness curves for shales (o), breccias (o), and calcilithites (o), Upper Shales Formation.



Plate 37. Graded top of breccia bed. Upper Shales,
Praz de Lys.



Plate 38. Dark grey calcareous shales, Upper Shales,
Roc d'Enfer. The prominent hand in the
lower/middle part of the outcrop is about
20 cm. thick.

more organic material, clays, or carbonate content.

4. Sandy siltstones.

These have the composition of an immature calcarenitic subgreywacke (Folk, 1964). Each bed is about 1 cm thick, and is graded from medium sand to very fine silt (FIG. 53). The clasts are mostly quartz with a lesser amount of carbonate rock fragments, and some metamorphic rock fragments (FIG. 54). These thin beds occur one on top of the other with no interbeds, for thicknesses of up to 9 metres. They are found only within the Upper Shales and are presumed to have formed by deposition from thin turbidity currents. Grading is of variable degree - there is generally a sharp upward change from fine to coarse, then a gradual fining up to the next bed.

3. Limestones.

Towards the top of the Upper Shales beds of dark grey (weathering pale grey) micritic limestone appear. These are identical to the limestones which form much of the Upper Breccia Formation and herald the change back to carbonate sedimentation. No breccias of the type found in the Upper Breccia occur in the Upper Shales. The transition to the Upper Breccia is made by the gradual appearance of micritic limestones. In addition there are one or two graded beds of gravelly calcareous mudstone, with fine-grained limestone forming the matrix - although some of the clasts attain fine granule size, the bulk of this rock is mud and sand (Plate 39).

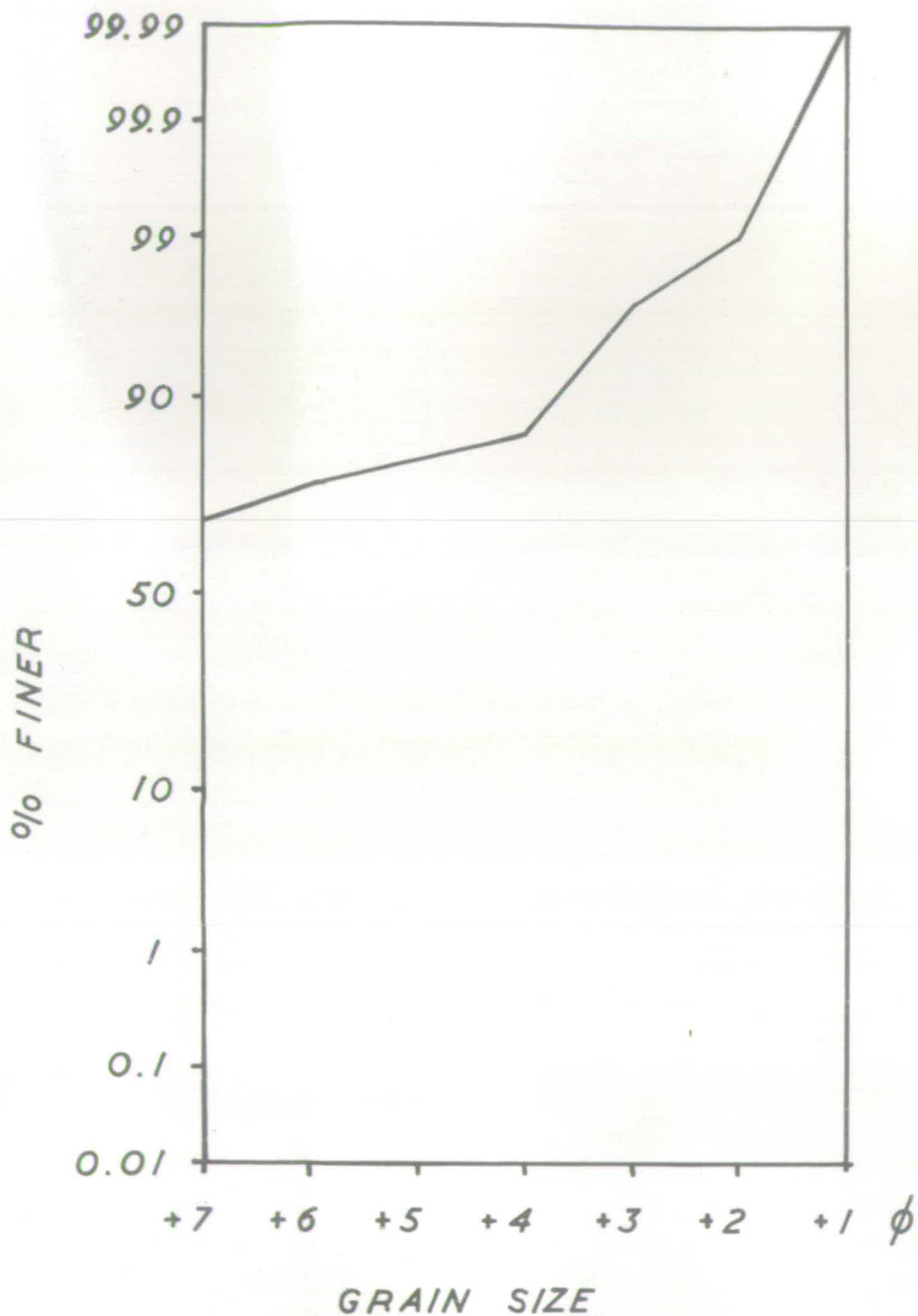


FIG. 53. Cumulative frequency/ grain size curve for graded subgreywacke in the Upper Shales.

The data are uncorrected and derived from point count analyses.

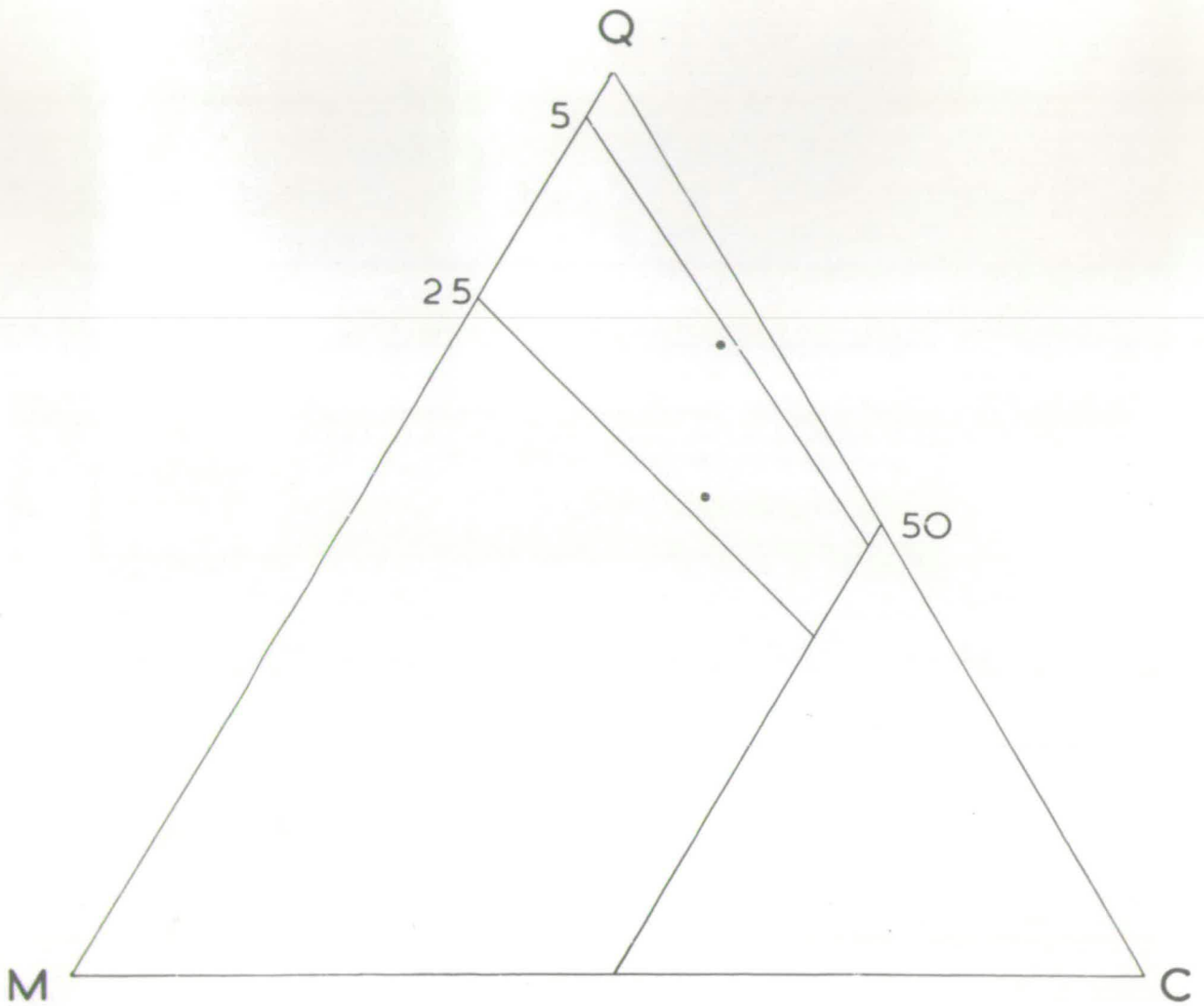


FIG. 54. Lithological analyses of graded siltstones, Upper Shales.

Q = Qtz. + qtz. + chert; M = Met. RF's; C = carbonate RF's.



Plate 39. Gravelly calcareous mudstone, graded, with parallel lamination at the top. Upper Shales, Praz de Lys.



Plate 40. Well-graded breccia. Upper Breccia Formation. Praz de Lys.

6. Lateral relationships of the Upper Shales with other formations.

Since the upper and lower boundaries, particularly the lower, are transitional, a lateral transition from the Upper Shales to the Lower Breccia is a possibility. The great thickness of the Lower Breccia (1300 m) and small thickness of Upper Shales (250 m) at Praz de Lys, compared with 300 m for the Lower Breccia and 300 m for the Upper Shales at Roc d'Enfer led Schroeder (1939) to suggest a lateral transition from one to the other. This seems to be confirmed by a study of the rocks themselves. At Praz de Lys the sequence is as follows:-

Upper Shales

Lower Breccia Flysch facies

Lower Breccia Breccia Facies

while at Roc d'Enfer:-

Upper Shales mainly red and green mudstones.

Upper Shales thin, fine-grained calcilithites and thick calcareous shales.

Lower Breccia breccia facies.

The type of sequence found in the flysch facies of the Lower Breccia has already been described. A section in the lower part of the Upper Shales at Roc d'Enfer consists of a few thin granule breccias, and sand grade calcilithites which grade to pelite. The 12.40 m thick section has gravel-sand/pelite in the proportion of 30%/70%, while in the flysch facies of the Lower Breccia at Praz de Lys, the corresponding proportions are 84%/16%. The breccias in the Upper Shales section are, with one exception (with a thickness of 1.30 m), all less than a metre in thickness, and comprise only 20% of the total measured thickness.

The breccias at Praz de Lys are often thicker than a metre and form about 40% of the measured thickness. The thickness-frequency distribution of the granule/sand/silt calcilithites at Roc d'Enfer differs from the section measured at Praz de Lys by having a greater proportion of thinner beds (FIG. 55). The section at Roc d'Enfer contains no red and green mudstones or thick beds of calcareous shales, in fact it is similar to any of the sections in the flysch facies of the Lower Breccia, apart from the thin bedding, lack of breccias, and large proportion of pelite. Although there is evidence for such a lateral transition, it is by no means the normal situation e.g. from Praz de Lys, both the Lower Breccia and the Upper Shales thin to the ESE, and at La Biolle the Upper Shales disappear completely while the Lower Breccia passes into the Lower Shales. Thus, since the marked lateral passage at Roc d'Enfer seems the exception rather than the rule it may be more convenient to think of the lower part of the Upper Shales at Roc d'Enfer as being a particularly thin-bedded, fine-grained representative of the Lower Breccia flysch facies. Further to the north-east, Chessex (1959) did not report a transition from the Upper Shales to the Lower Breccia. This may have been because he identified a lower, coarse-grained facies and an upper fine-grained facies in the Lower Breccia, and considered the red and green mudstones as an essential constituent of the Upper Shales, and even in the south-western part of the nappe there is no evidence of a transition from the Lower Breccia to the part of the Upper Shales containing these mudstones.

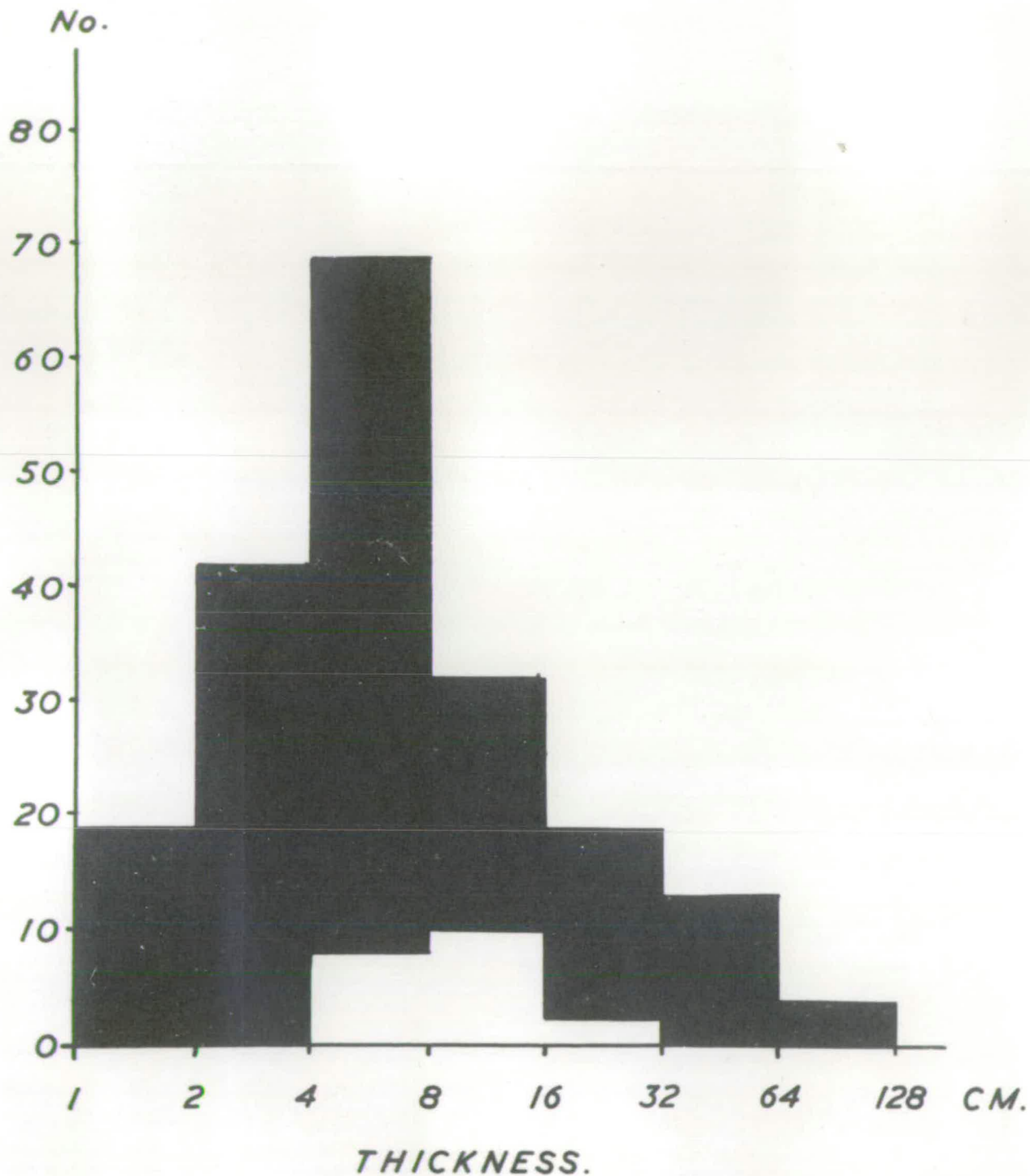


FIG. 55. No.frequency/thickness histogram for calcilithites at Praz de Lys (black), and at Roc d'Enfer (white). Flysch facies, Lower Breccia.

The possibility of a transition from the Upper Shales to the Upper Breccia is less likely. The actual vertical change from one to the other is rapid at any one locality. Although some of the beds of limestone common in the Upper Breccia may occur in the Upper Shales, once deposition of the breccia beds of the Upper Breccia Formation has commenced, there are no more sediments of the Upper Shales type.

7. Thickness variations in the Upper Shales.

Mapping of the formation thickness for the Upper Shales reveals no straightforward variation (FIG. 51). In the south-west part of the area there is maximum development around Roc d'Enfer with thinning to the south-west, south, and south-east. However, if the lower part of the Upper Shales at Roc d'Enfer is grouped with the Lower Breccia then there is no thickness change except for a thinning to zero in the region of la Biolle. Thinning of the Lower Breccia from Praz de Lys to la Biolle is not compatible with Schroeder's (1939) suggestion of the Upper Shales thinning as the Lower Breccia thickens and vice versa. In the north-east part of the area, a 200 m thickness of Upper Shales at Roc de Tavaneuse thins to zero at Les Lindarets, a distance of 5 km; a further 3 km to the south-east the thickness has increased to 40 m at Avoreaz. At Les Lindarets (FIG. 56), a flysch-type sequence of graded calcilithites with sole markings passes up into thick, coarse breccias (of Lower Breccia type) with cross-stratification and laminated sandy lenses. This is directly overlain by breccias of Upper Breccia type. Since the Upper Shales are absent, and the uppermost

First breccia in Upper Breccia Fmn.

Topmost breccia in Lower Breccia Fmn.

sandy layer in breccia

gravelly graded beds.

graded calcilithites of the flysch facies.

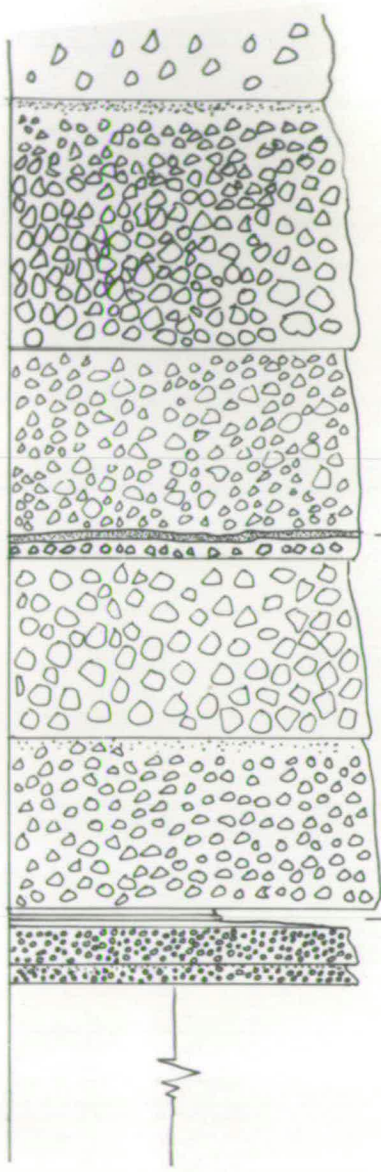


FIG. 56. Top of Lower Breccia, and base of Upper Breccia, with Upper Shales absent. Les Lindarets.

Lower Breccia is unusual in having bottom current structures and in being coarser than usual, it has been assumed that during deposition of the Upper Shales elsewhere, this must have been a local topographic high where there was no deposition. A similar, comparable thickness variation, with a north-west to south-east thinning then thickening has been described from the area further to the north-east (Chessex 1959, and FIG. 57). Thus the locus of minimum deposition was along a line from the southeast side of Mont de Grange to Les Lindarets and then to La Biolle. There was thickening to the north-west and south-east of this line.

Palaeogeographic reconstructions from the Lower Breccia indicated a landmass to the west and north of the depositional area which supplied great thicknesses of breccia spreading out from Praz de Lys and the Roc de Tavaneuse area. Later, during deposition of the flysch facies of the Lower Breccia, there was some supply from the south-west, particularly of the thinner beds. The main question is whether south-west or north-west supply predominated during the deposition of the Upper Shales. Unfortunately, palaeocurrent indicators are absent from the Upper Shales. The type of thickness variation described above, when considered in relation to the inferred position of the land mass, cannot be directly related to distance from source. It seems rather, that the sediment distribution may have been controlled largely by the bottom topography. This topography ~~which~~ could not have been directly related to the thickness of the Lower

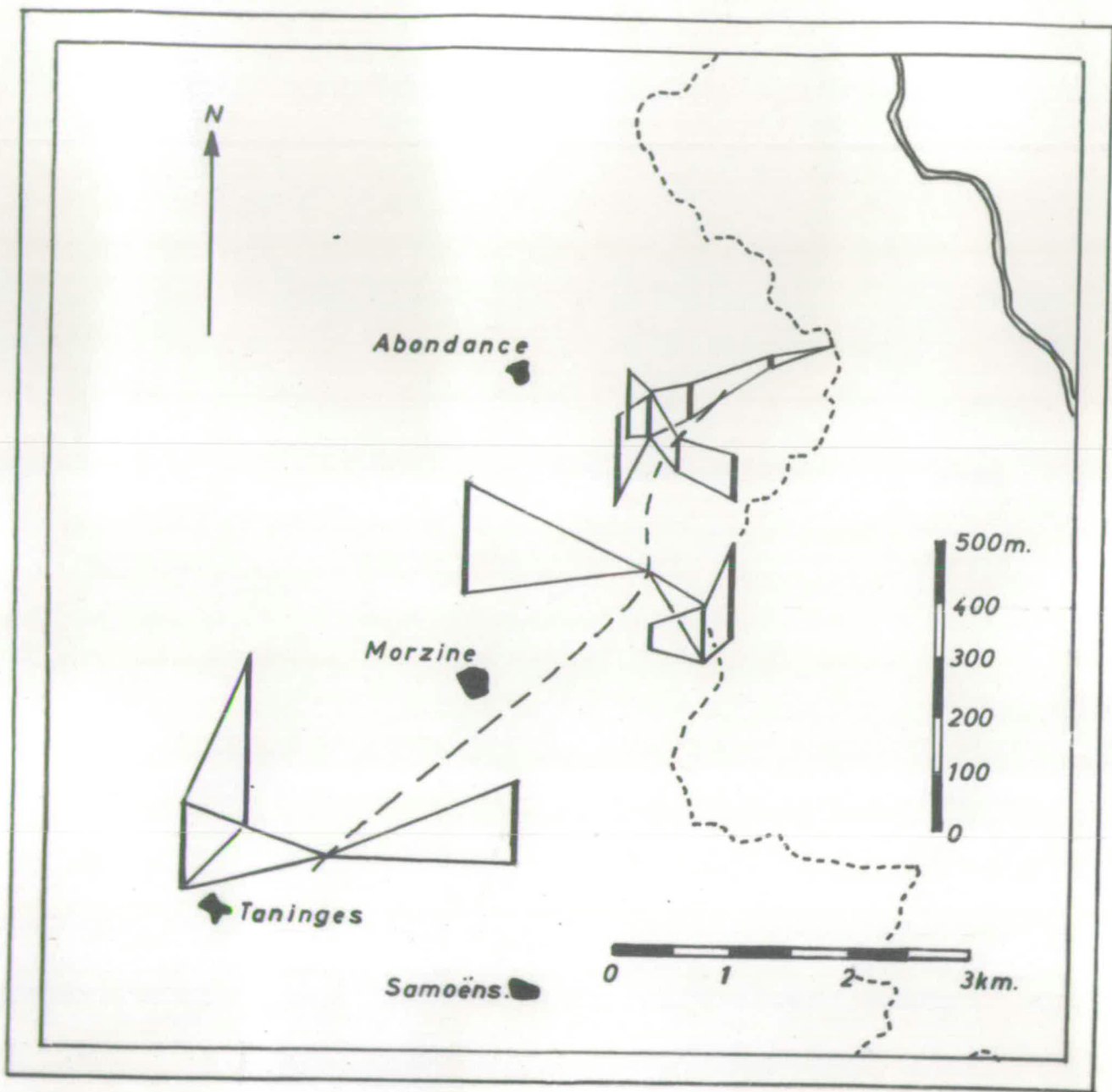


FIG. 57. Thickness variations in the Upper Shales. Data from present study and from Chessex (1959).

Breccia deposits, since the thicknesses of the Lower Breccia and the Upper Shales are not complementary. Thus during deposition of the Upper Shales, there must have been a south-west to north-east submarine rise where deposition was at a minimum. In such a case sediment supply may have been from the south-west and/or the north-west. To the north-east of the present study area, Chessex (1959) has found a thinning of the formation to the north-east, but he admits that it is partly a result of tectonics, and cannot be used as an indicator of distance from source.

IV. THE UPPER BRECCIA FORMATION.

The Upper Breccia Formation overlies the Upper Shales, except at Les Lindarets where it follows the Lower Breccia with a sharp boundary (FIG. 56). On the basis of fossil evidence from the limestones in the formation it is considered to be U. Jurassic - Cretaceous in age (Chessex 1959). It is defined by the presence of the breccias, which are markedly different from those in the Lower Breccia and the Upper Shales, the main difference being the large proportion of calcareous muddy matrix in the breccias of the Upper Breccia.

1. The lower boundary of the formation.

The base of the formation is considered to be marked by the position of the lowermost muddy breccia at any one locality. This is unsatisfactory as a stratigraphic marker, or a time horizon, because of the limited lateral extent of individual breccia beds, but the striking textural differences between the breccias of the Upper and Lower Breccia Formations make it the most practical method in the field. Even at Les Lindarets, where the Upper Shales Formation is absent, and the top of the Lower Breccia is represented by a thick breccia, the overlying breccia can be attributed to the Upper Breccia purely on the basis of the greater proportion of matrix. Similarly, at Praz de Lys, the topmost bed in the Upper Shale Formation is a breccia of Lower Breccia-type, but again textural differences assign the overlying breccia to the Upper Breccia Formation. Breccia beds of Upper Breccia-type have not been seen in the Upper Shales, although limestones, gravelly calcareous mudstones, and calclithites of the types

found in the Upper Breccia Formation do occur towards the top of the Upper Shales. This partial vertical transition seems to have been completed by the time the first breccia bed of Upper Breccia-type arrived at any one locality, for no Upper Shale sediments occur interbedded with these breccias. The first appearance of Upper Breccia-type limestones, gravelly calcareous mudstones, and calcilithites may be as much as 15 or 20 metres below the first of the Upper Breccia-type breccias, giving some idea of the thickness of the transition zone.

2. Thickness of the formation.

Since, in the present study area, the top of the Upper Breccia Formation has often been removed by erosion (at Avoreaz and Roc de Tavaneuse) its true thickness cannot always be appreciated. However, measurements by Lugeon (1896), Schroeder (1939), Chessex (1959), and the present study suggest a north-west to south-east, or north to south thinning (FIG. 58). The thicknesses shown in FIG. 58 represent the thickness in which breccias are found only. Previous descriptions Lugeon (1896), Schroeder (1939), Arbenz (1947), and Chessex (1959) have included in the Upper Breccia Formation, considerable thicknesses of limestone (of the same type as is found interbedded with the breccia beds) which occur above the main sequence of breccias, so that the figures given for the present study are considerably less than those for other reports.

3. Lithologies.

There are three lithological types in the Upper Breccia,

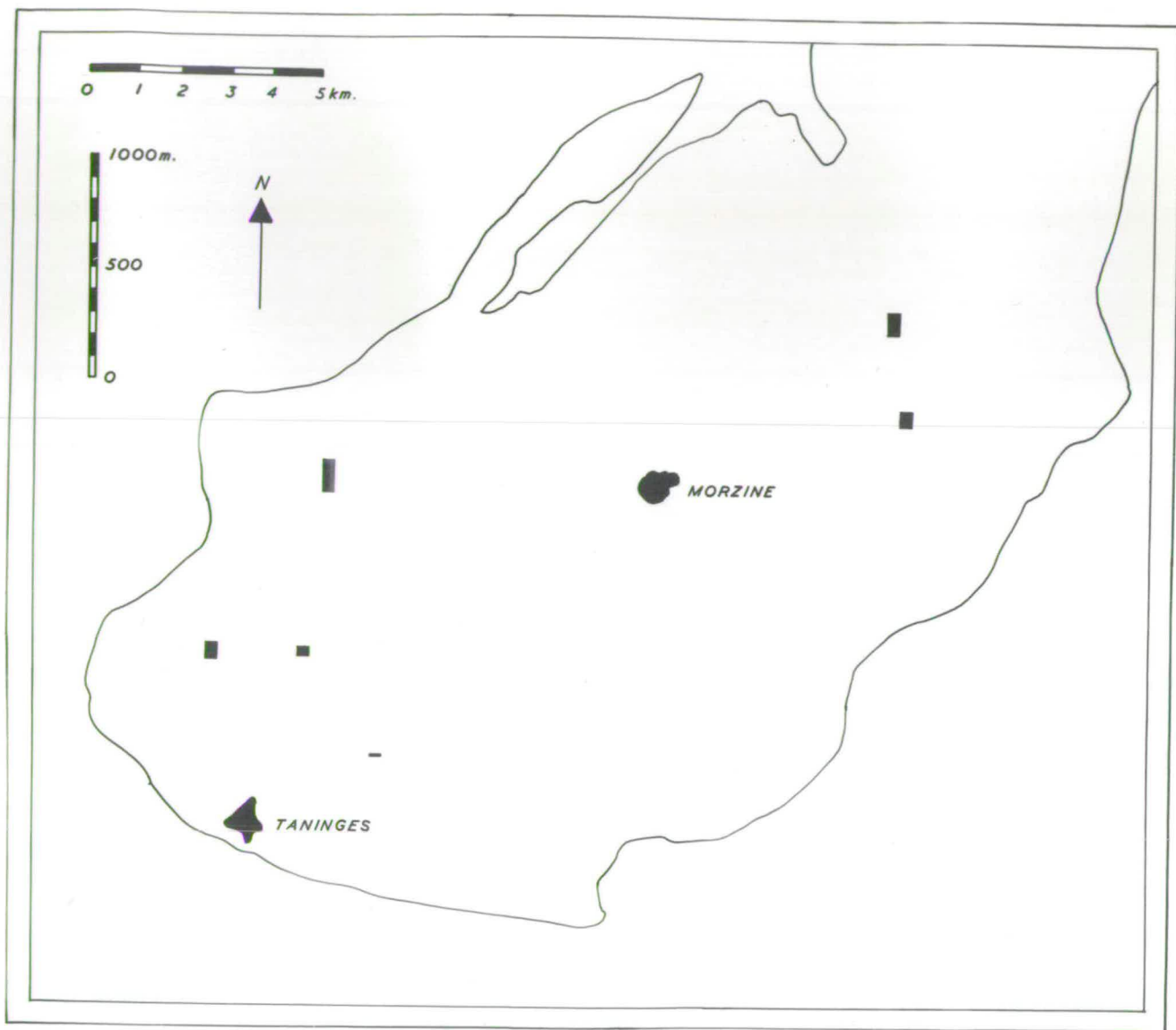


FIG. 58. Thickness of Upper Breccia Formation at different localities.

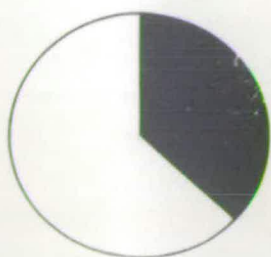
differentiated principally in terms of grain size:-

- (a) Breccias (Pl. 40).
- (b) Gravelly calcareous mudstones (Pl. 39), and calcilithites.
- (c) Limestones.

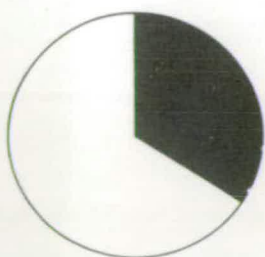
The respective proportions of these types, by thickness in the measured sections, are 47%, 2%, and 51%. However, since the breccias are more resistant to weathering and therefore more likely to be exposed than the limestones, it is likely that the true proportion of the limestones is greater than that measured. Chessex (1959) suggests that the limestones form 80% - 90% of the formation, but this includes limestones overlying the breccias as well as those interbedded with them. The true value (for the Breccia Formation as defined in the present study i.e. only that thickness which contains the breccias) is likely to lie somewhere between these two estimates.

(a) Breccias.

The breccias may have as much as 40% calcareous muddy matrix (FIG. 59). Texturally, they would belong to the 'muddy gravel' class of Folk's (1964) scheme. They may be up to 2500 cm thick, but usually have thicknesses of around 100 cm to 500 cm (FIG. 60). The breccia beds are lensoid, and of limited lateral extent. One bed at Praz de Lys shows considerable variation in both thickness and maximum clast size in a distance of only 300 metres along the strike (FIG. 61). On a larger scale, also at Praz de Lys, the proportion of breccia beds and the thickness of individual beds decrease from north to south (FIG. 62). The best exposures of breccia at Praz de Lys are on the slopes to



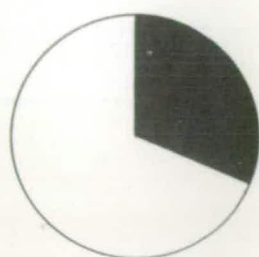
A.



B.



C.



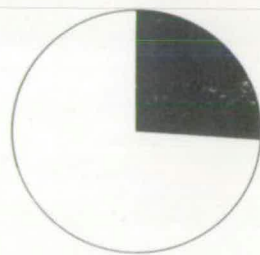
D.



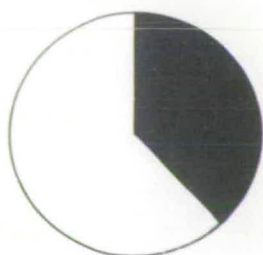
E.



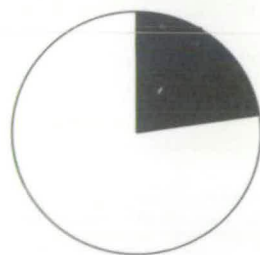
F.



G.



H.



J.

FIG. 59. Proportion of muddy matrix in breccias; Upper Breccia.
Matrix proportion in black.

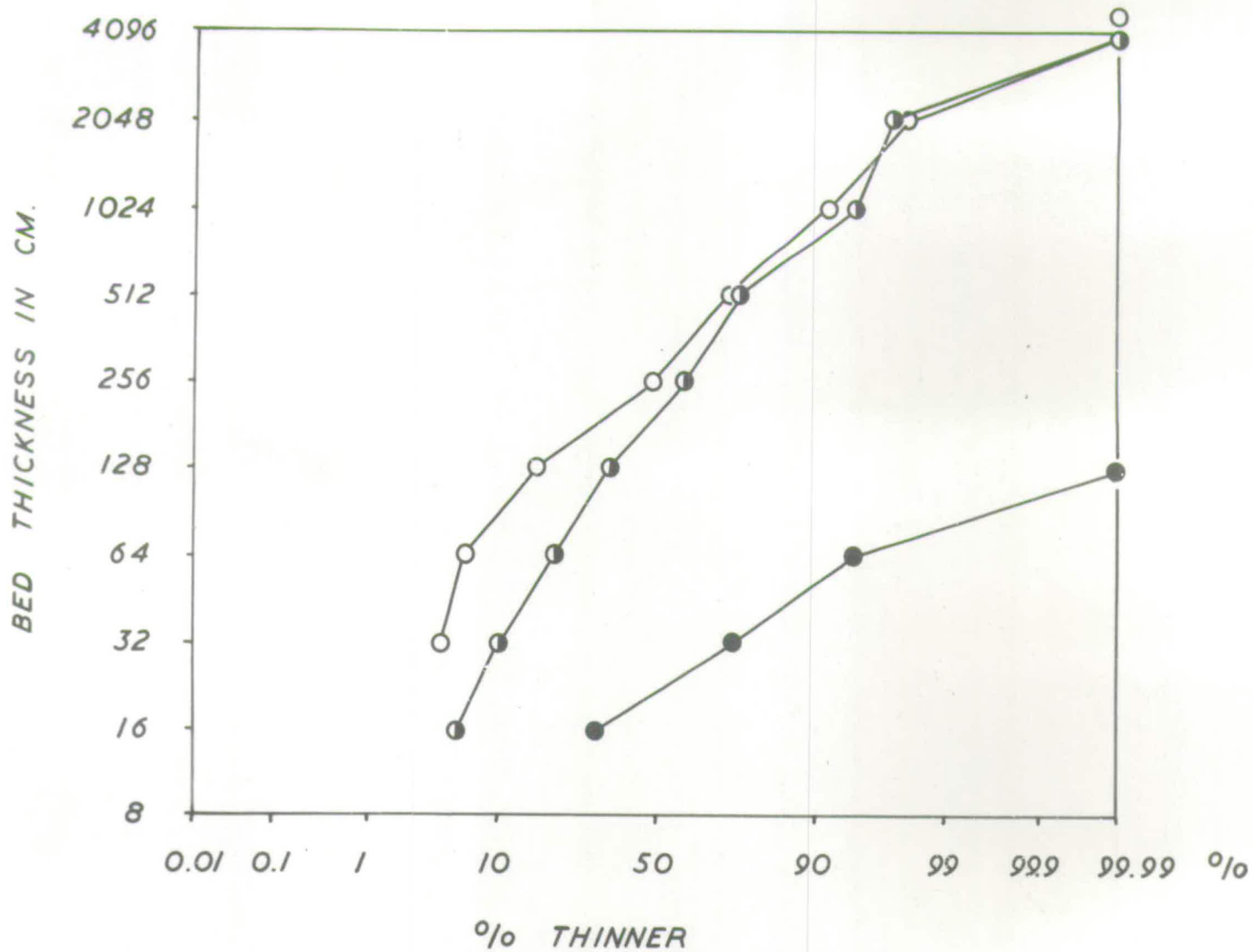


FIG. 60. Cumulative frequency/bed thickness distributions for limestones (o), breccias (o), and calcilithites (o), in the Upper Breccia.

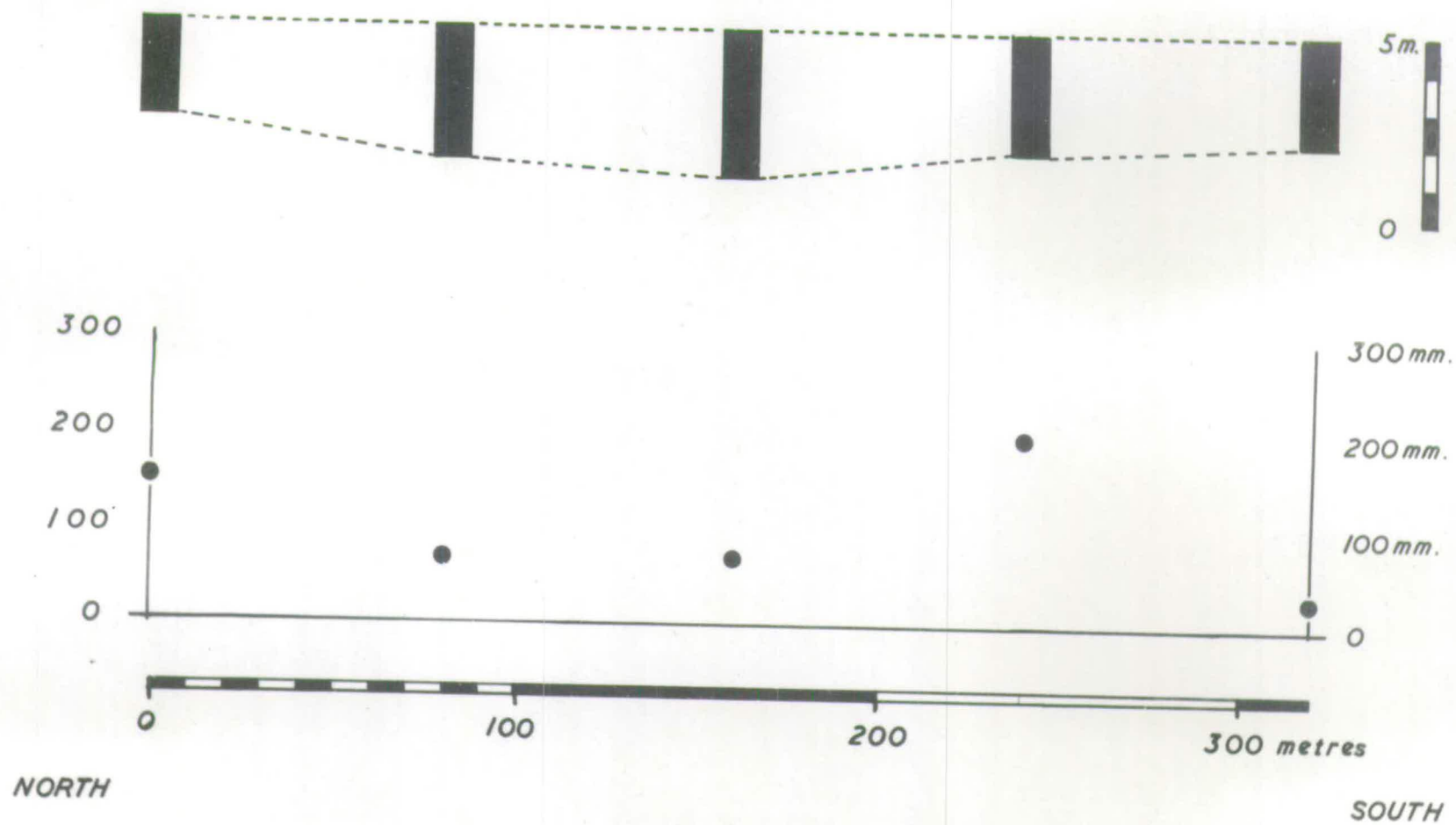


FIG. 61. Variation in bed thickness, and maximum clast size in one breccia bed, Upper Breccia, Praz de Lys.

Sections through the breccia pile, Upper Breccia Formation, Praz de Lys

NORTH

SOUTH

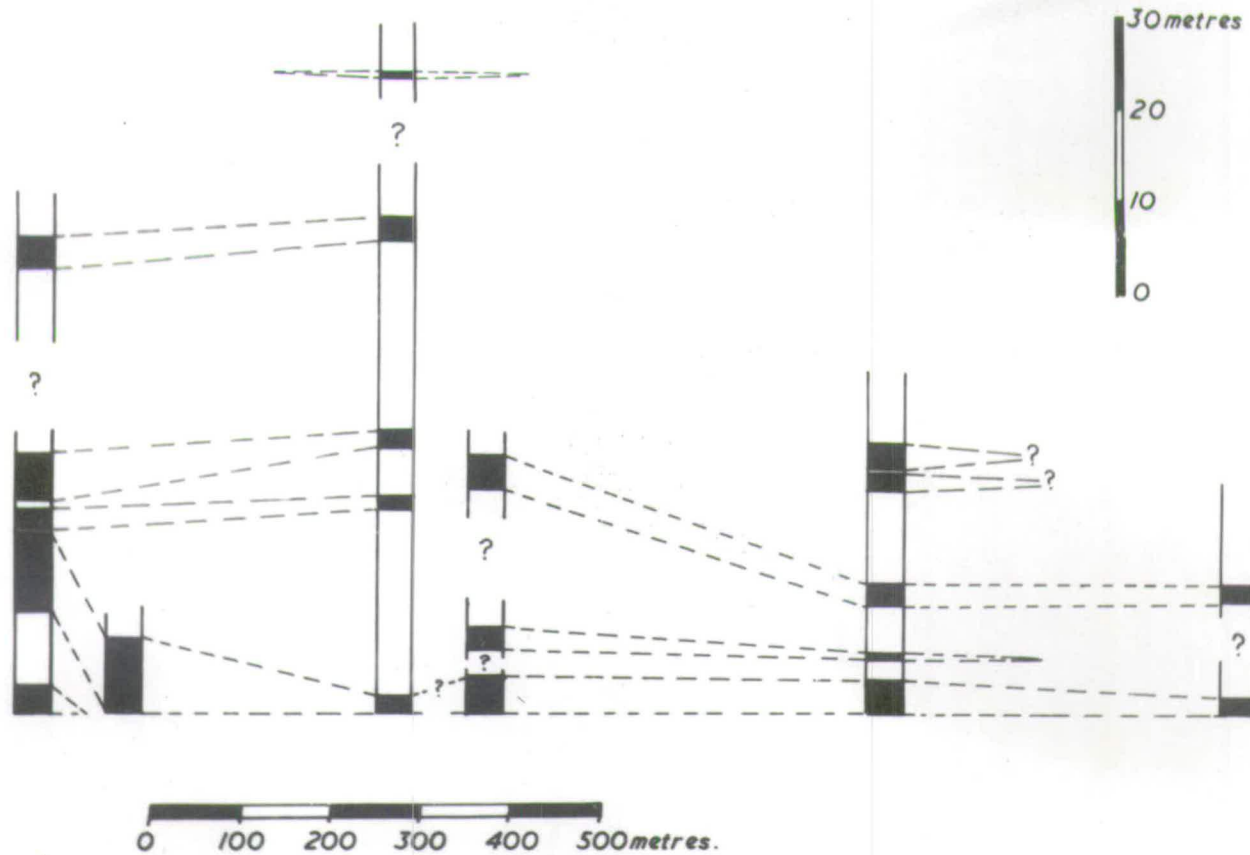


FIG. 62. Sections through the Upper Breccia breccia pile at Praz de Lys, showing decrease in thickness of breccias from north to south.

the east of Lac de Roi, where the beds dip to the east. The disappearance of breccia beds, and the variations in thickness can be traced over a distance of 1500 metres along the strike.

(1) Clast sizes in the breccias.

Clasts may be up to 1000 mm in diameter but are usually less than 250 mm (FIG. 63). Individual beds have poor sorting of clasts (FIG. 64 curve A), and the clast size distribution of the whole bed (clasts + matrix) is generally bimodal (FIG. 64 curve B). Maximum clast sizes show considerable variation over the whole area, but there is no clear trend (FIG. 65). However, evidence from the Praz de Lys area has shown that although the distribution of breccia beds and the number of breccia beds in the local sequence suggest an origin to the north, study of the variation in maximum clast size in one breccia bed does not reveal a uniform decrease from north to south (FIG. 61).

There is a correlation, significant at the 5% level, between maximum clast size and bed thickness for the breccias (FIG. 66). This is presumed to indicate that, subject to availability, the coarsest clasts could only be supplied along with the larger amounts of sediment as would be the case with a mud flow deposit.

The clasts in the Upper Breccia breccias may be up to 40% siliceous types (schists, quartzites, sandstones, vein quartz), the remainder being predominantly calcareous (dolomite and limestone). The siliceous clasts are in

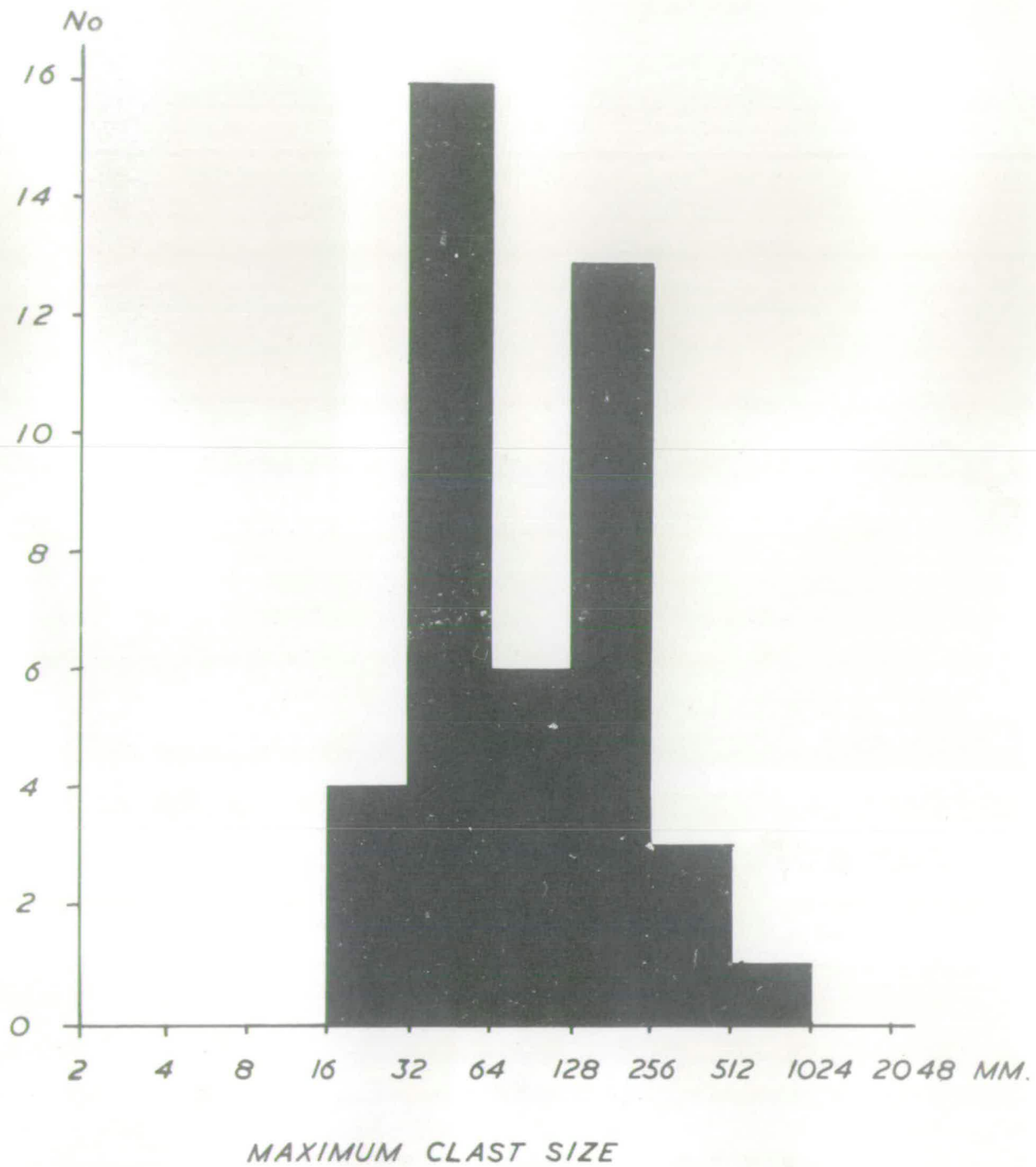


FIG. 63. Maximum clast size in breccias, Upper Breccia.

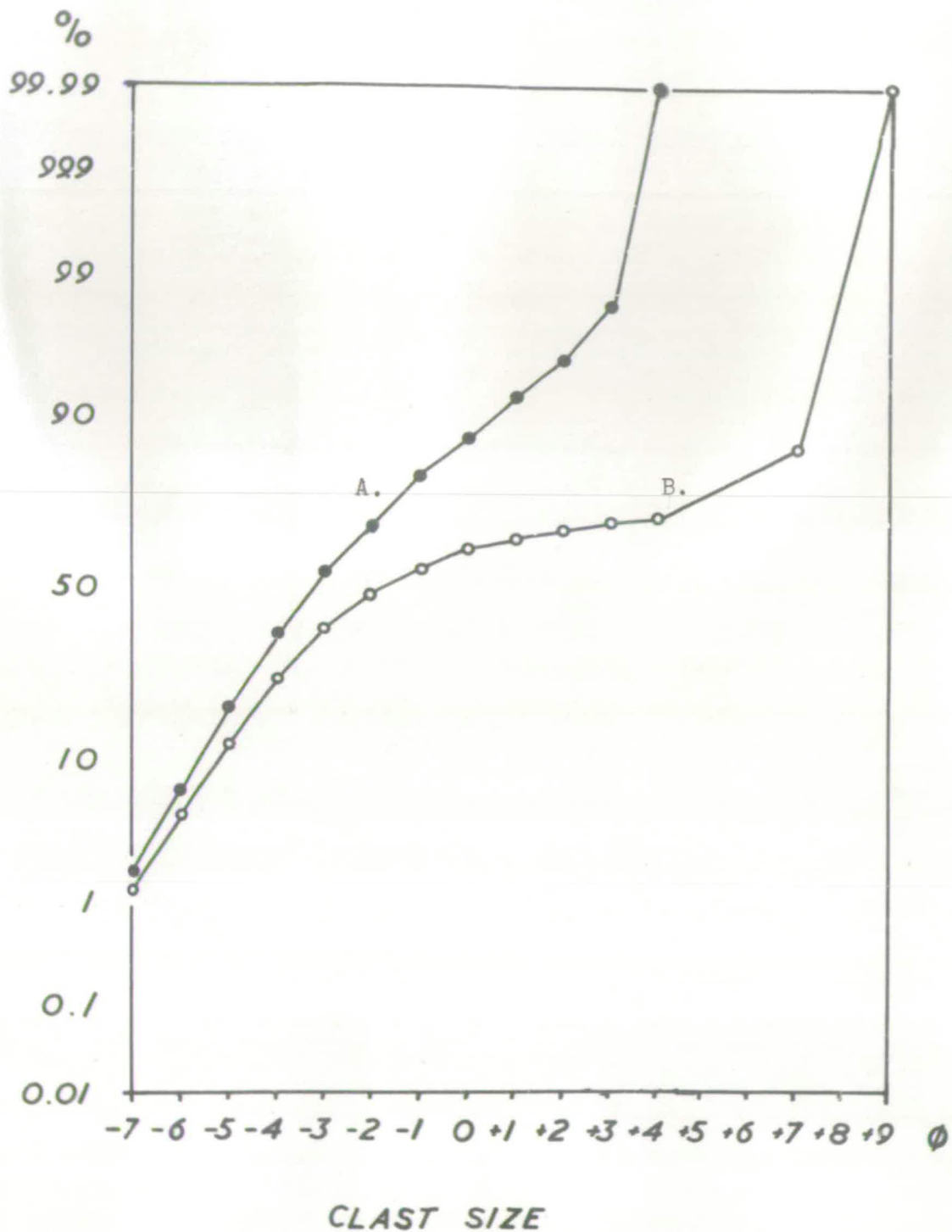


FIG. 64. Clast size distribution in a breccia, Upper Breccia, Praz de Lys.

Curve A - excluding matrix; curve B - including matrix.

The data are uncorrected and derived from point count analyses at the outcrop.

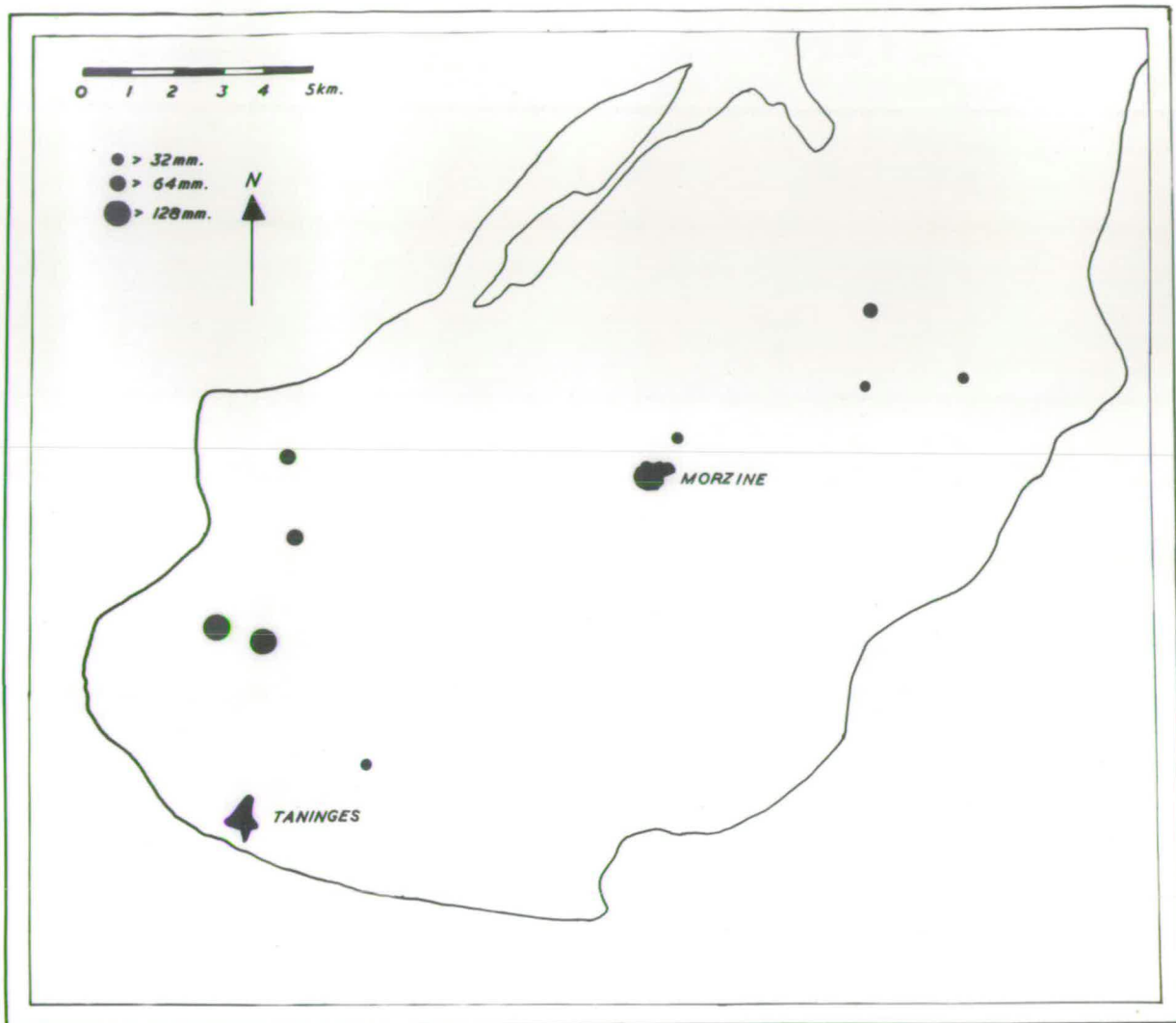


FIG. 65. Geographical variation in maximum clast size in breccias, Upper Breccia.

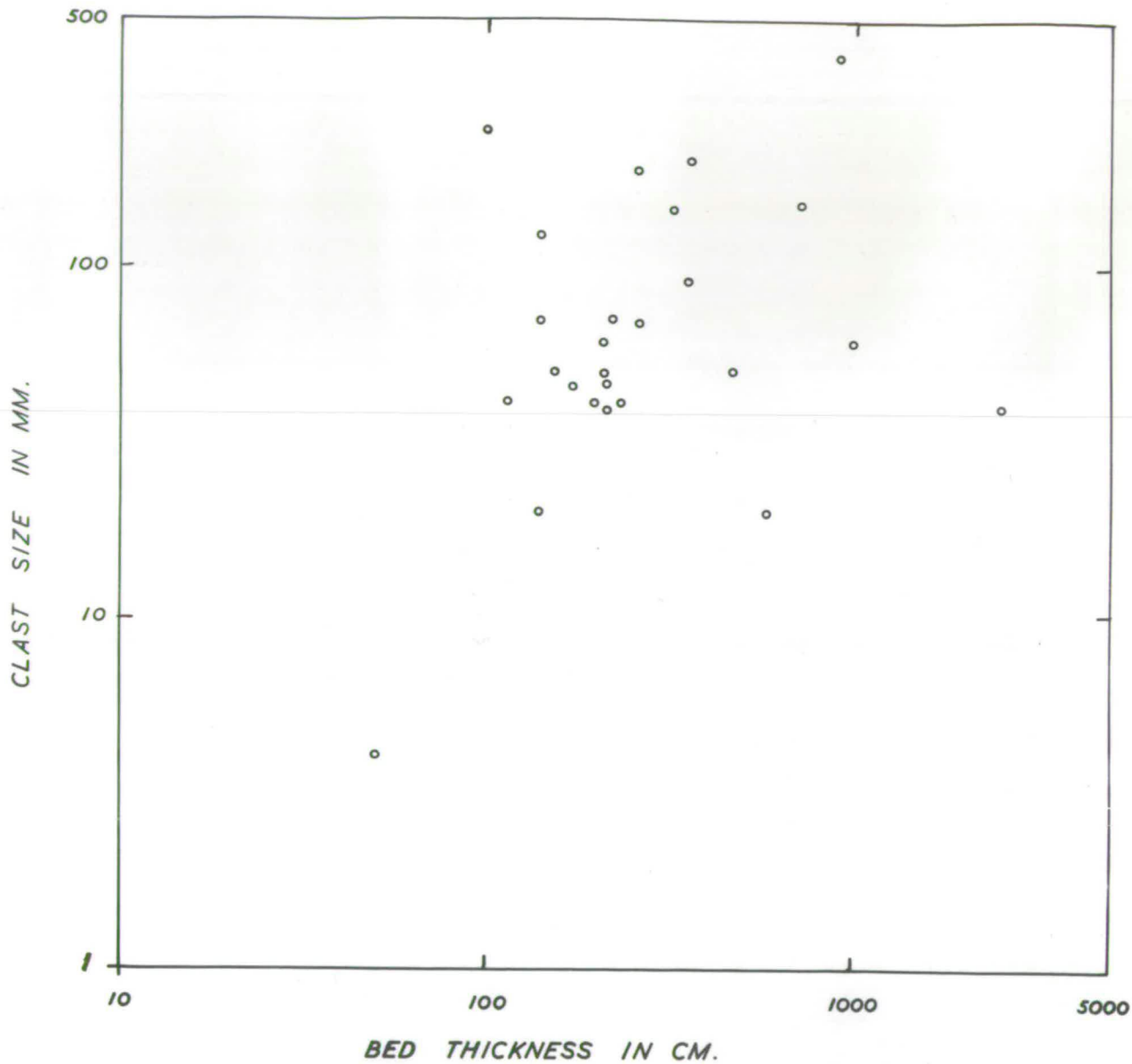


FIG. 66. Maximum clast size plotted against breccia thickness for Upper Breccia breccias.

general less well-rounded than the carbonate ones (FIG. 67). The modal class for siliceous clasts is 0.15 to 0.25, and that for carbonate clasts is 0.25 to 0.40 (values from roundness scale of Pettijohn 1957). This is similar to the result obtained for roundness analyses in the breccias of the Lower Breccia (FIG. 12), and suggests that distance of transport by currents, or period spent in a current-swept area was limited.

(ii) Structures in the breccias.

(1) External structures.

Generally the lower surfaces of breccia beds are very flat. Only one example to the contrary was seen and this was at the base of a thick graded breccia at Roc d'Enfer (Plate 41). Here, clasts from the base of the breccia are mixed with the calcareous mud of the underlying limestone, over a thickness of about a metre. The mud was obviously in a highly fluid state when the breccia was deposited. Since these structures are uncommon, either the mud was compacted rapidly after deposition, or the breccias did not usually have strong erosive power. 'Strength' of erosive power is purely relative and cannot be demonstrated from field evidence anyway, more so if the first statement (of the mud being highly cohesive) holds. It is known that carbonate muds have a low 'plasticity index' (Boswell 1960) i.e. after deposition they pass through the fluid and plastic

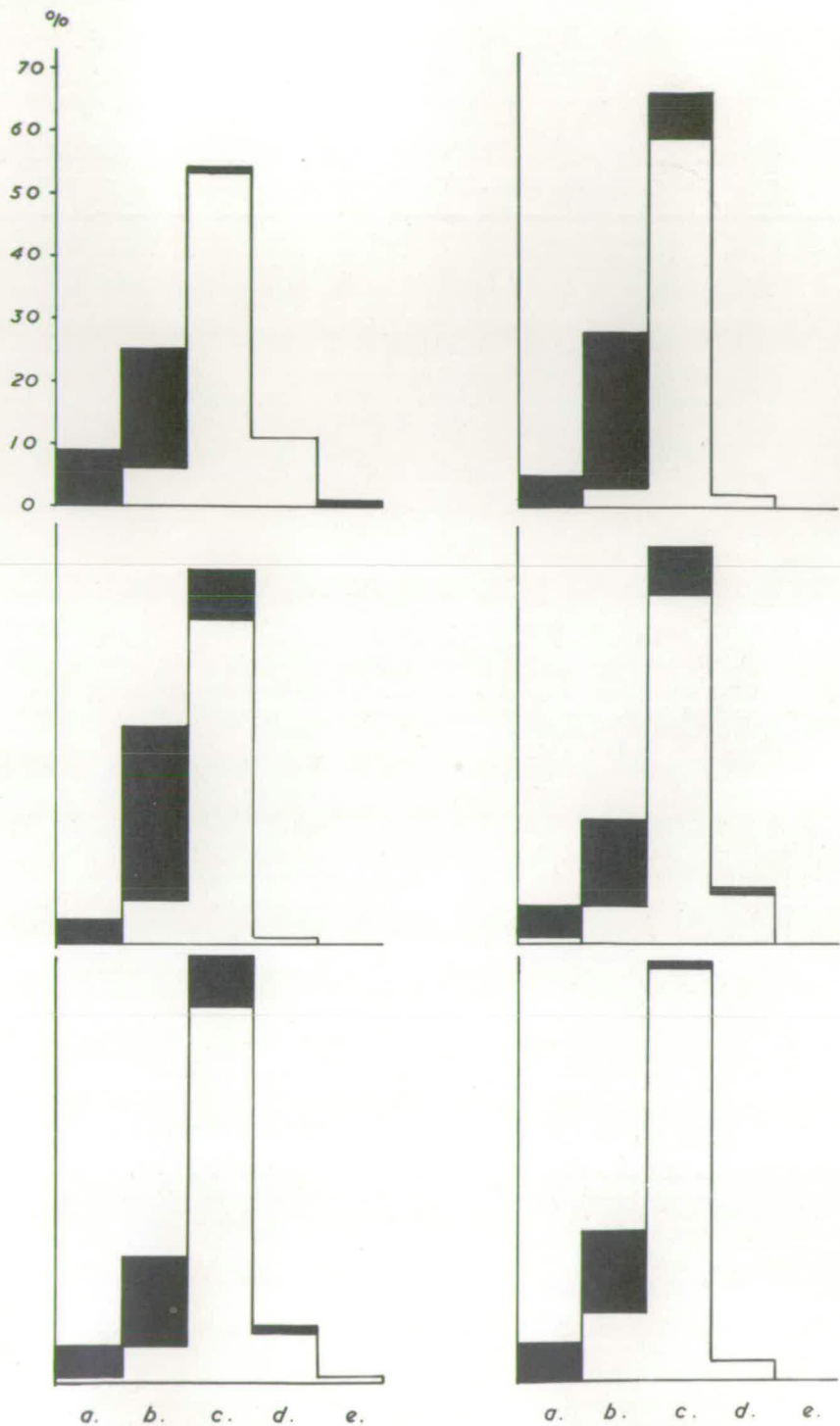


FIG. 67. Rounding of clasts in breccias, Upper Breccia. Siliceous clasts - black; carbonate clasts - white. Roundness classes of Pettijohn (1957), increase in rounding from a to e.



Plate 41. Erosion by breccia. Upper Breccia, Roc
d'Enfer. Breccia - B; Limestone - L.



Plate 42. 'Coarse tail' grading in gravelly calcareous
mudstone. Upper Breccia, Avoreaz. Scale
in cm.

stages to a compacted condition, more quickly than do clayey muds. This may be one positive reason for lack of erosion structures at the bases of breccias, for, even if the breccias had negligible erosive power, if the lime mud bottom was not usually cohesive, the weight of cobbles and boulders would most likely cause extensive load casting in a floor with fluid or plastic properties. Load structures are common below the conglomerates of a non-calcareous flysch sequence in Chile (Scott 1966), and have been reported from pebbly mudstones by Crowell (1957). The complete lack of such structures below the breccias of the Upper Breccia Formation leads me to suggest that the lime mud bottom was usually highly cohesive.

(2) Internal structures.

The principal structure is grading (Plate 40), which is widespread and well-developed. An analysis of grading in one 350 cm bed was carried out using the same method as was employed for the bed in the Lower Breccia (p. 14). A seven (rows) by eight (columns) grid, with a spacing of 500 mm, was used, giving measurements of 280 clasts. Because of the wide range in clast sizes, the data were tested for homogeneity of variances using Bartlett's test (Bartlett 1937). This revealed that the data were not amenable to an Analysis

of Variance. However, plotting the row/column means in control chart form, with the 5% probability limits indicated, reveals the contrast between vertical and horizontal variations in clast size (FIG. 68). Only in the vertical sense is there a significant variation. If these beds are accepted to be some type of mud flow deposits, then the analysis shows that the distribution of clast sizes within the beds was controlled almost entirely by gravity, as opposed to differences of viscosity and density at different parts of the flow in a lateral sense. Grading occurs in some very thick beds and at Roc d'Enfer, one bed grades from cobble size material (200 mm) to silty pelitic limestone, over a thickness of 850 cm.

Inspection of many beds, and a series of clast size analyses for seven levels through a graded breccia bed (FIG. 69), show that the sorting of the clasts (matrix excluded) does not deteriorate towards the base of the bed. Since sand, and even granule grade clasts are not normally trapped between the cobbles and pebbles at the bases of breccia beds, separation of the clasts must have been well-developed during transport, and there could not have been strong turbulence in the flow to destroy the size grading.

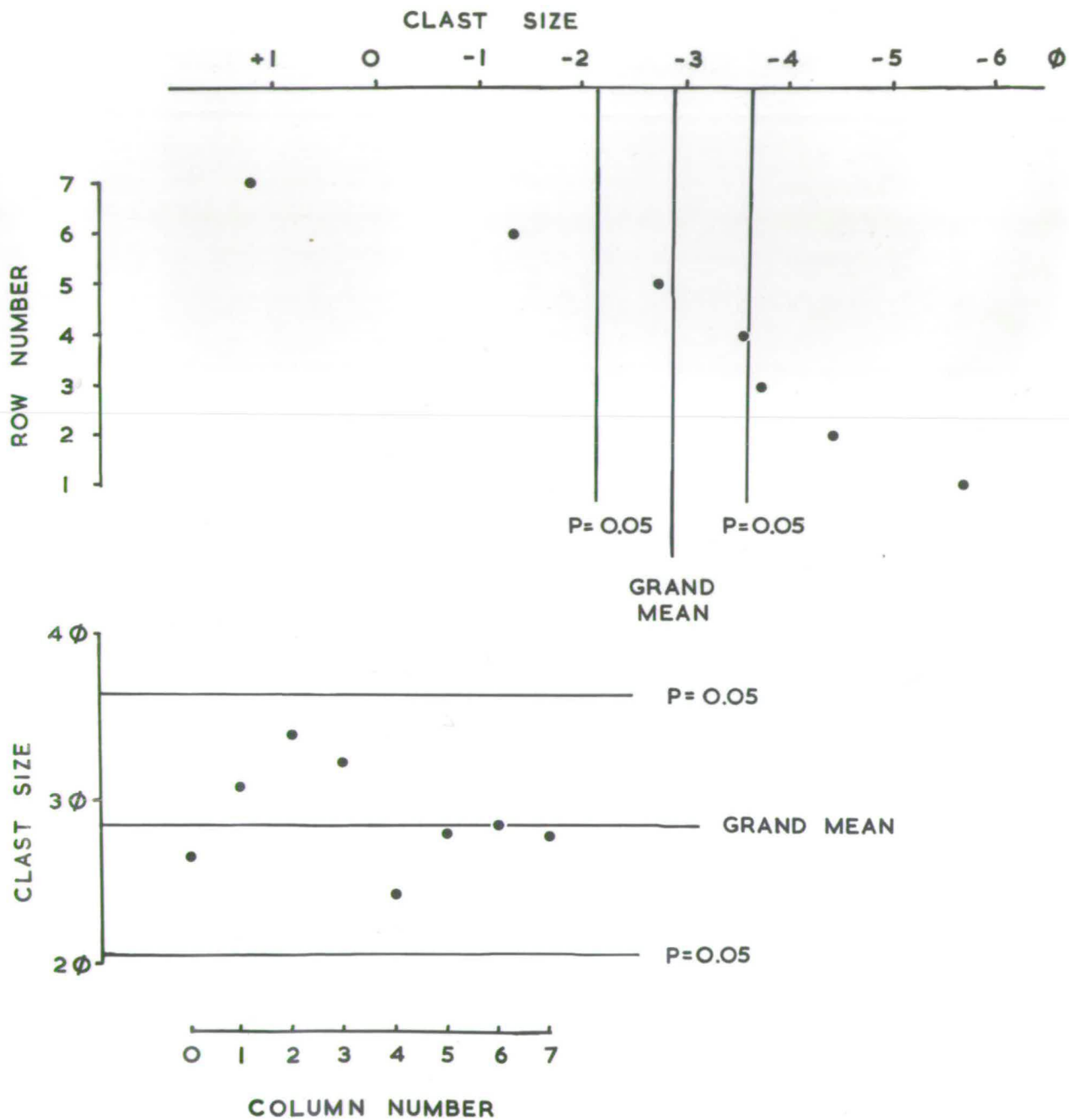


FIG. 68. Mean clast size in rows/columns for a breccia, Upper Breccia, plotted in control chart form, with the 5% probability limits indicated.

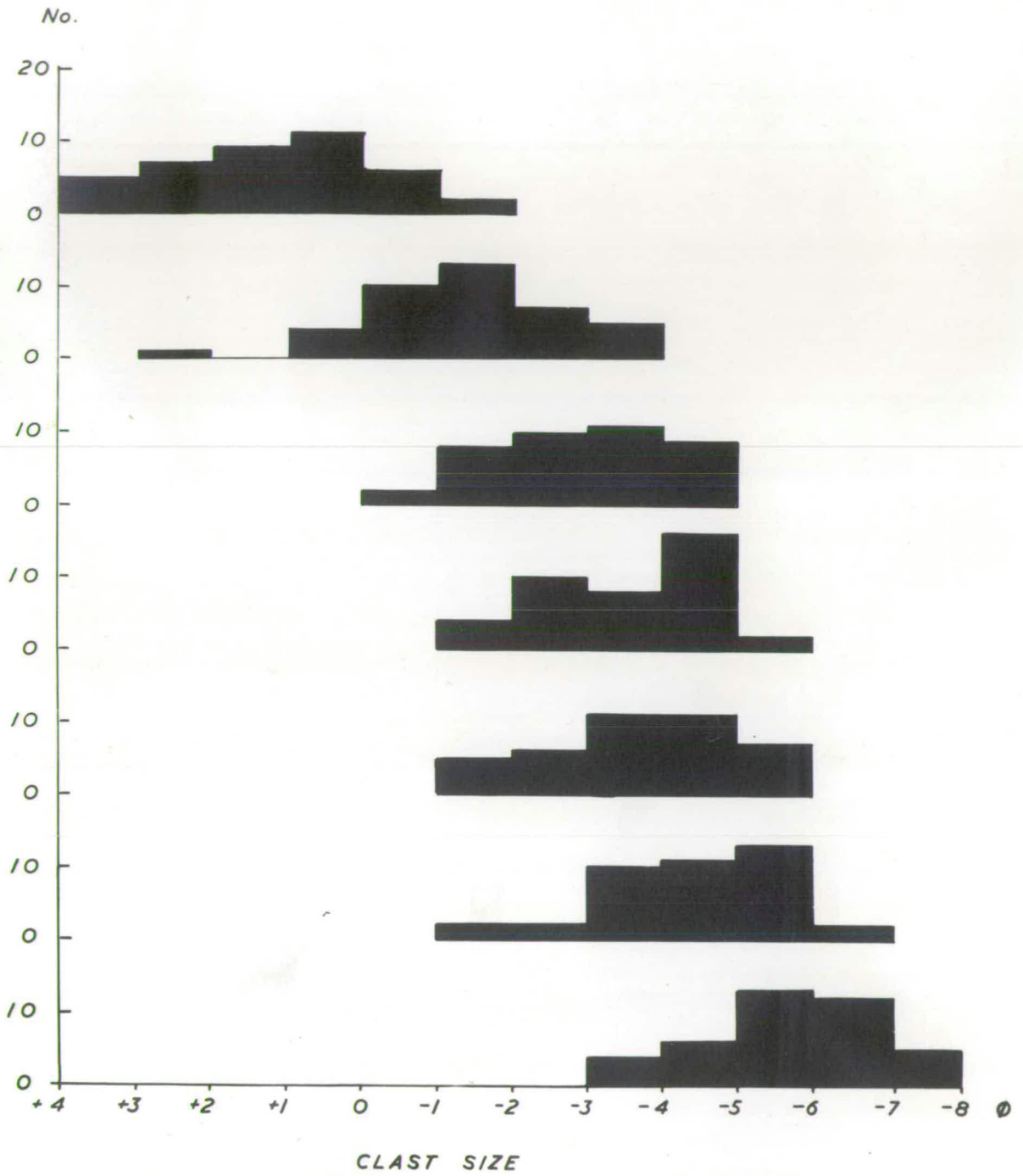


FIG. 69. Clast size distribution at seven levels through a graded breccia bed, Upper Breccia.

It seems, therefore, that the grading is a result of differential settling of clasts, rather than gradual deposition from a waning current. This is in favour of a fairly viscous fluid, and a possible mud flow origin.

No parallel, or cross-lamination has been found in the breccias, even at the tops of beds.

b) Gravelly calcareous mudstones and calcilithites.

These beds form a very small proportion by thickness (2%) of the formation. They are all less than 100 cm thick, usually around 20 cm (FIG. 60), and they are generally graded.

(i) Gravelly calcareous mudstones.

These are more common than the calcilithites. They are similar to the breccias apart from the smaller sizes of the phenoclasts and the greater proportion of calcareous mud matrix. The most common structure is grading and the only type seen in these beds is a gradual decrease in the proportion of clasts from bottom to top of the bed (Plate 42) - "coarse tail" grading of Middleton (1967) found to occur in high concentration experimental density flows. The clasts in a bed are sometimes aligned parallel to the bedding in a form of lamination (Plate 42). The topmost part of a bed may also be laminated - parallel lamination only was seen. Usually, however, the beds are unlaminated, and their upper parts are composed of

lime mud (similar to that in the limestones of the formation) which sometimes contains some rock fragments or pellets. The mud matrix is generally less abundant near to the base of a bed, especially if the clasts are very coarse (Plate 43). The matrix may have a lumpy aspect and the tendency to form "matrix balls". These are well-developed in one particular bed (Plate 44). They form irregular, rather well-rounded shapes but with numerous indentations from surrounding clasts. They are up to 40 mm long. They are composed of calcareous mud and the material can be seen to pass between and around clasts from one matrix lump to another (Plate 45). This calcareous mud must have been in a fluid/plastic state during transport and deposition of such a bed. Although the bed is well-graded, the lumps of matrix do not show a size grading so their density must have been relatively low. However, their plastic state is attested by their slight deformation but lack of disintegration. At the same time, some of the mud must have been sufficiently fluid to mix with the clasts and form a normal matrix.

(ii) Calclithites.

These are generally thin, less than 10 cm, and have little mud matrix but may grade up into mud. They often contain granules or even pebbles at the base grading rapidly upwards to sand then mud. They may



Plate 43. Graded bed showing clasts in contact near to the base. Upper Breccia, Avoreaz. Scale in cm.

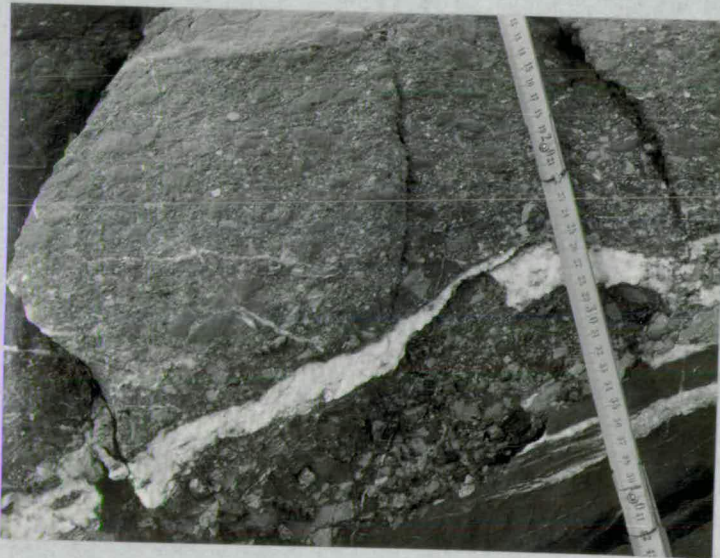


Plate 44. Graded bed showing matrix lumps. Upper Breccia, Avoreaz. Scale in cm.

well be the results of deposition from muddy suspensions which were very fluid so that most of the clasts settled to the base of the bed to form a deposit low in mud content. The common lack of a relatively thick mud layer above the beds suggests that if they did form in this way then the muddy current must have normally passed by to be deposited elsewhere.

These two rock types occur together, and their association suggests that the calcilithites could represent the deposits from lower density flows than the ones which produced the gravelly calcareous mudstones.

No cross-lamination was seen in these beds, perhaps flows were too viscous, or composed of unsuitable grain sizes, or lacking suitable grain sizes in sufficient quantities, or perhaps deposition was generally too fast.

c) Limestones.

These make up at least 51% of the formation. They vary in thickness up to 30 metres (FIG. 60), and they are generally structureless. They are dark grey when fresh, but weather to a very pale grey colour. They are generally entirely micrite, but sometimes, especially near to the tops of breccia beds there may be an admixture of sand or silt size terrigenous grains, pellets, oolites, and microfossils (generally forams).

The relationship between breccia beds and limestones.

The breccia beds grade up into limestone by gradual disappearance of all clasts. When a breccia overlies limestone, the boundary is clear-cut (Plate 46).

4. The matrix of the breccias.

The matrix of the breccias is often micrite (Plate 47), and similar to the fine-grained limestones (Plate 48) that are interbedded with the breccias. More commonly, however, an admixture of quartz, carbonate grains, pellets, and oolites, and even fossil fragments makes it coarser (Plate 49). The matrix in a bed is normally less abundant near to the base than it is towards the top.

5. The behaviour of the matrix and the clasts and the origin of the breccias.

The overall poor sorting of the breccias, the high content of muddy matrix, the good clast-size grading with an upward passage into homogeneous limestone, and the lack of current structures even towards the tops of the beds, combine to suggest that the breccias may have been deposited from mud flows. Field evidence suggests that near to the site of deposition at least, the erosive power of the flows was limited and seldom disturbed underlying sediment. The good separation of the different clast sizes suggests that for most of the beds the fluidity of the fine-grained parts must have been within fairly constant limits, for although cobbles and pebbles may occur in contact near to the base of the bed with only interstitial matrix, the granule and sand clasts near to the top of

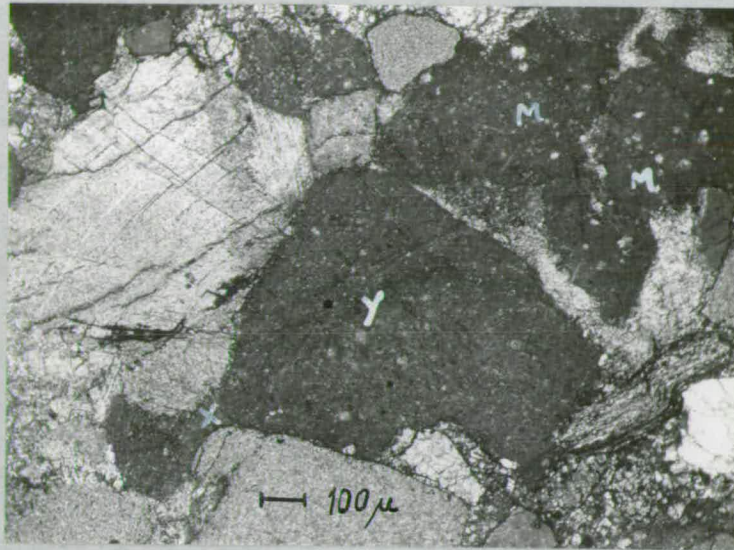


Plate 45. Thin section of bed shown in Plate 45.
Matrix (M) passes between clasts at X, and
forms lumps at Y.



Plate 46. Breccia overlying limestone with clean contact.
Upper Breccia, Praz de Lys.

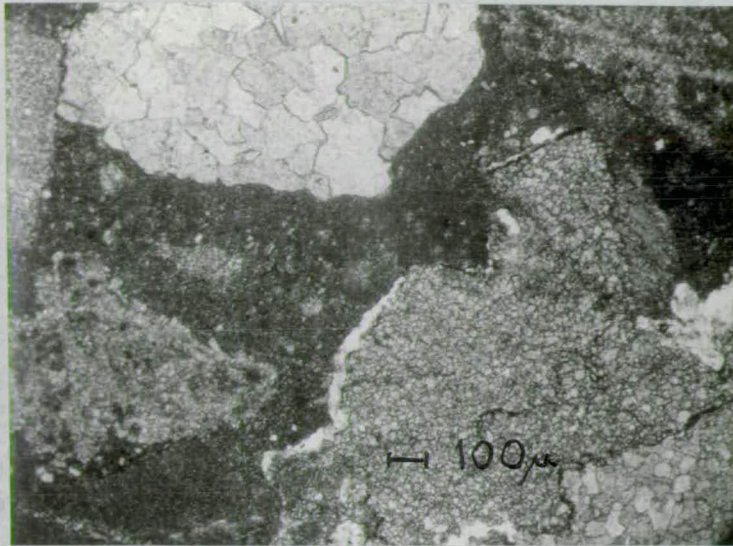


Plate 47. Micrite matrix in breccia. Upper Breccia.

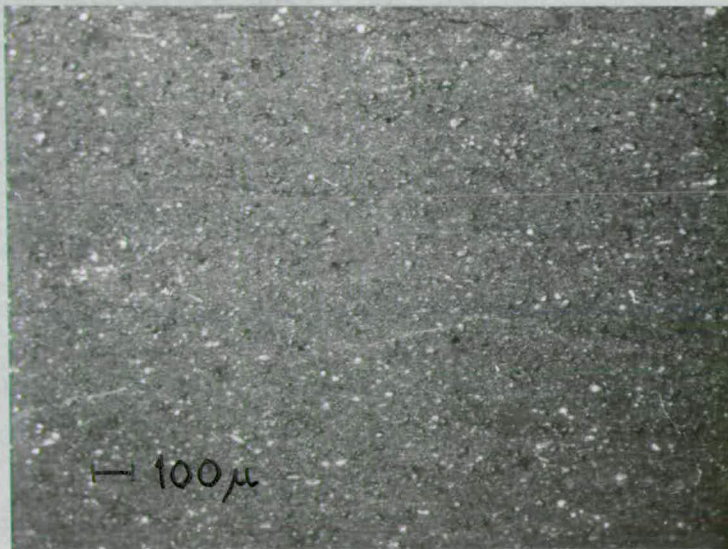


Plate 48. Limestone. Upper Breccia.

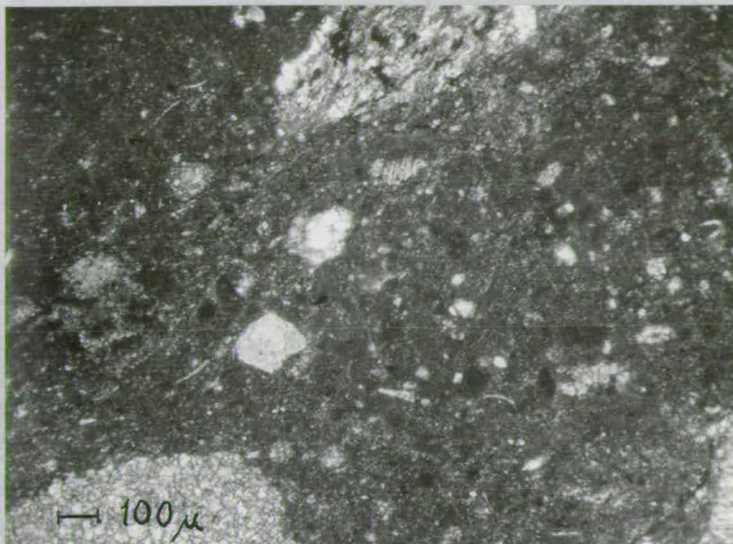


Plate 49. Coarse admixture in micrite breccia matrix.
Upper Breccia.



Plate 50. Limestone lump in breccia. Upper Breccia,
Praz de Lys.

the beds are often completely separated by finer matrix. The good separation of particles, and lack of contortion features suggests that the formation mechanism for the beds was a flow rather than a slide or slump. However, there are several details which cannot be fully explained by a simple mud flow type of origin. These involve the following phenomena:-

1. Lumps of limestone from the same sequence occur in the breccia beds (Plate 50).
2. Lumps of breccia occur in limestone beds (Plate 51).
3. Lumps of fine breccia occur in coarser breccia (Plate 52).
4. Lumps of breccia matrix occur in the breccias (Plate 53).

These shall now be considered separately.

1. Lumps of dark grey micrite, which is commonly interbedded with the breccias may occur as cohesive undeformed lumps within a breccia bed (Plate 50), as cohesive but deformed lumps (Plate 54), and as partially cohesive lumps which have been penetrated by breccia clasts (Plate 55). These three types of occurrence exhibit elastic, plastic, and partially fluid rheologic states respectively. These limestone lumps must have been derived from the limestone beds within the sequence, probably not near to the site of deposition since evidence of erosion of the limestone substrate by the breccias is not common. It is not surprising that these limestone clasts should have varying states of



Plate 51. Breccia lump in limestone. Upper Breccia, Uble.



Plate 52. Lump of fine breccia in coarse breccia. Upper Breccia, Praz de Lys.



Plate 53. Lump of breccia matrix in breccia. Upper Breccia, Praz de Lys.



Plate 54. Deformed limestone lump in breccia. Upper Breccia, Praz de Lys.



Plate 55. Limestone lump (M) penetrated by breccia clasts. Upper Breccia, Praz de Lys.

cohesion, for if they are plucked from near the surface they will still be passing through the early stages of compaction. Any material assimilated by the breccia which was not at all cohesive would of course be distributed among the clasts as matrix. The large size of some of the limestone lumps, and their position in the fine top parts of the breccia, suggests that their density must have been close to that of the matrix of the flow. Since terrigenous clasts of similar size are found usually at the bases of beds, it is unlikely that the cause was that the matrix density was high.

2. The converse situation, where lumps of breccia occur within massive limestone was seen at only one locality on the mountain of Uble. Large slabs of breccia up to 2 or 3 metres across, occur within a massive micrite limestone. The breccia has clasts up to 100 mm in size and a calcareous mud matrix. The boundaries of the slabs are clear-cut, and the clasts are not dispersed in the surrounding limestone. This is an example of the elastic behaviour of lumps of breccia. Unfortunately, it was not possible to tell if the surrounding limestone had moved in lumps since slip planes could not be discerned in the homogeneous material. It is assumed that the lumps of breccia slid into position on a floor of lime mud, and that the surface of the mud was probably fairly fluid. There was no evidence of disturbance in the limestone beneath the breccia slabs. Lack of evidence of internal movement in the breccia lumps further confirm that this is an example of introduction of the lumps by a slide mechanism - although they

may have formed originally by deposition from a flow.

3. The occurrence of large, relatively fine-grained lumps of breccia within a coarse, graded, breccia (Plate 52) is a result of either:-

1. Incorporation by the flow of an already cohesive lump of finer breccia

or,

2. The operation of some (unknown) mechanism within the flow which causes a cloud of finer breccia to accumulate and eventually settle at a level where coarser clasts predominate.

Since the main trend in clast distribution within a breccia bed is towards a bottom to top grading, and the clouds of finer breccia can be as much as one metre long, the second possibility is considered the less likely of the two.

4. The mode of occurrence of the matrix in the breccias is variable. It is found as a continuous matrix and, less commonly, as lumps and patches. It thus shows two states of rheotropy - plastic and fluid. Both such states may occur in a single bed (Plate 45).

The problem of formation of grading in such a bed is thought to be resolved as follows. If the flow was dilute with respect to clasts, then settling of the coarsest clasts would not necessarily be greatly hindered by the presence of large lumps of mud of approximately the same density as the fluid phase in the flow. Although some of the smaller clasts

would be able to settle past the lumps, movement of others would be restricted by the lumps and some may even adhere to the lumps. Final settling and compaction of the bed would produce a graded bed with few matrix lumps at the bottom, but more as the clast size decreased further up in the bed. In the uppermost part of the bed where clasts are absent, it is impossible to differentiate matrix which was originally fluid, from that which was initially plastic.

Except in one case (at Uble) the clasts show complete mixing with the matrix to the extent of being able to form grading. This means that the history of the deposits could not normally have involved extensive periods as say interbedded gravels and muds before they were disturbed to form a flow, for then the deposits would be likely to show evidence of broken and disrupted bedding, and more limestone and breccia lumps than do actually occur. It is known from experiments that lime muds are compacted, and pass through their plastic state much more quickly than do clay muds (Boswell 1960). Thus lime muds may be solid quite near to the sediment surface, and erosion of more than the surface layers would produce compacted limestone clasts. These do occur, but they are by no means equal in volume to the amount of lime mud in the matrix of the breccias. The muddy matrix must have been supplied largely in a fluid state. Matrix material may have been capable of remaining fluid for a longer time if there was an admixture of coarser material such as pellets, fossil fragments, and rock fragment grains.

Since the origin of the breccias by sliding of interbedded gravels and muds is considered unlikely because of lack of disrupted bedding etc. it is thought that the flows may have started as submarine rock slides which incorporated matrix from the underlying floor by a process similar to that envisaged by Crowell (1957) for the origin of pebbly mudstones. This is thought to be the only means of transport which would explain the dominantly fluid behaviour of the material.

The gravel in the breccias may have had a similar origin to the gravel which is found in the breccias of the Lower Breccia Formation. It is lithologically similar, though not identical; it occurs in similar sizes to the gravel material of the Lower Breccia, but with a tendency to be slightly finer; the rounding of the clasts is of a similar degree to those in the Lower Breccia. It may have accumulated initially then as a slope deposit of submarine talus, until disturbed either by some external cause, or simply by overloading to a point where it was no longer stable.

The original site of deposition of the gravel was presumably outside the final depositional area of the breccias, because all the breccias seen have a large percentage of matrix, and are usually graded. Even at Uble, the localization of the breccias in separate slabs with no isolated clasts in the limestone, and the mud matrix of the breccias, suggests that this may be the second, or even third, depositional site of the breccias.

V. PETROLOGY.

The sand and gravel grade rocks of the formations studied show three principal gross lithological variations. First of all, there is a marked textural change from the mainly coarse Lower Breccia deposits to the finer sediments of the Upper Shales, followed by the change back to the coarse beds of the Upper Breccia. This is accompanied by a compositional change from predominantly carbonate rocks in the Lower Breccia, to more siliceous types in the Upper Shales, and a return to carbonate compositions in the Upper Breccia. Finally, as indicated by Schroeder (1939), the types of rock fragments which are found in the breccias suggest that erosion in the source area progressed through a sedimentary cover of shales, limestones, and dolomites to underlying mica-schists.

The rocks are largely carbonates, and diagenetic effects create many difficulties in thin section analyses. Dolomitic and calcareous rock fragments, fossil fragments, and muddy calcareous material have often been replaced, to varying degrees, by crystalline calcite or dolomite. Partial or complete replacement of calcite and calcareous rock fragments by silica is also common. Stylolites at phenoclast boundaries often reveal that phenoclast material has been removed. Since few thin sections are free of some such alteration or replacement, a true calculation of the original composition of a complete rock is not always possible. However, fair estimates of the relative proportions of different rock fragment types, and principal mineral

constituents is generally possible, especially in field analyses of the breccias where the clasts are of pebble/cobble grade, and complete replacement or alteration of individual clasts is not likely.

1. The nature and origin of the clasts in the breccias and calcilithites.

The majority of the clasts are believed to come from a land-mass of Liassic, Triassic, and Hercynian Basement rocks. In the alpine region, typical rocks of these ages are:-

Liassic	-	black marly limestones; shaly marls; echinoderm limestones; siliceous limestones; black shales; sandstones.
Triassic	-	sandstones; dolomites; dolomitic limestones; marls.
Hercynian Basement	-	metamorphic schists.

The types of rock fragments found in the breccias, and their presumed ages are (after Schroeder 1939, and the present study):-

Lower Breccia.

1. Calcarenite.	Liassic ?
2. Lithic calcarenite.	Liassic ?
3. Micrite.	Liassic ?
4. Echinoderm Limestone.	Liassic ?
5. Dolomitic pel/biosparite.	Triassic
6. Dolomitic pel/biomicrite.	Triassic
7. Dolarenite (silt to sand grade).	Triassic
8. Calc-bituminous shale.	Liassic

- | | |
|--------------------------------|-----------|
| 9. Black shale. | Liassic |
| 10. Brown, organic rich shale. | Liassic |
| 11. Clayey siltstone. | Liassic ? |

No metamorphic rock fragments have been found in the breccia beds of the Lower Breccia Formation.

Upper Breccia.

- | | |
|--------------------------------------|----------------------|
| 1. Calc-bituminous shale. | Liassic ? |
| 2. Dolomite breccia. | Triassic |
| 3. Dolomitic pel/biosparite. | Triassic |
| 4. Dolomitic pel/biosparite. | Triassic |
| 5. Dolarenite (silt to sand grade). | Triassic |
| 6. Micrite. | Triassic ? Liassic ? |
| 7. Calcareous sandstone. | Triassic |
| 8. Orthoquartzite. | Triassic |
| 9. Metaquartzite. | Permian |
| 10. Quartz-mica-chlorite schist. | Permian |
| 11. Quartz-feldspar-chlorite schist. | Permian |
| 12. Quartz-garnet-mica schist. | Permian. |

As well as the contribution of rock fragments, there are also fossil fragments, ooliths, and pellets which tend to occur mainly in the finer sandy parts of the Upper Breccia breccias. These are probably derived from the littoral region during Upper Breccia times.

Many of the rock fragments, particularly the dolomitic types and some of the limestones, have a wide range in the

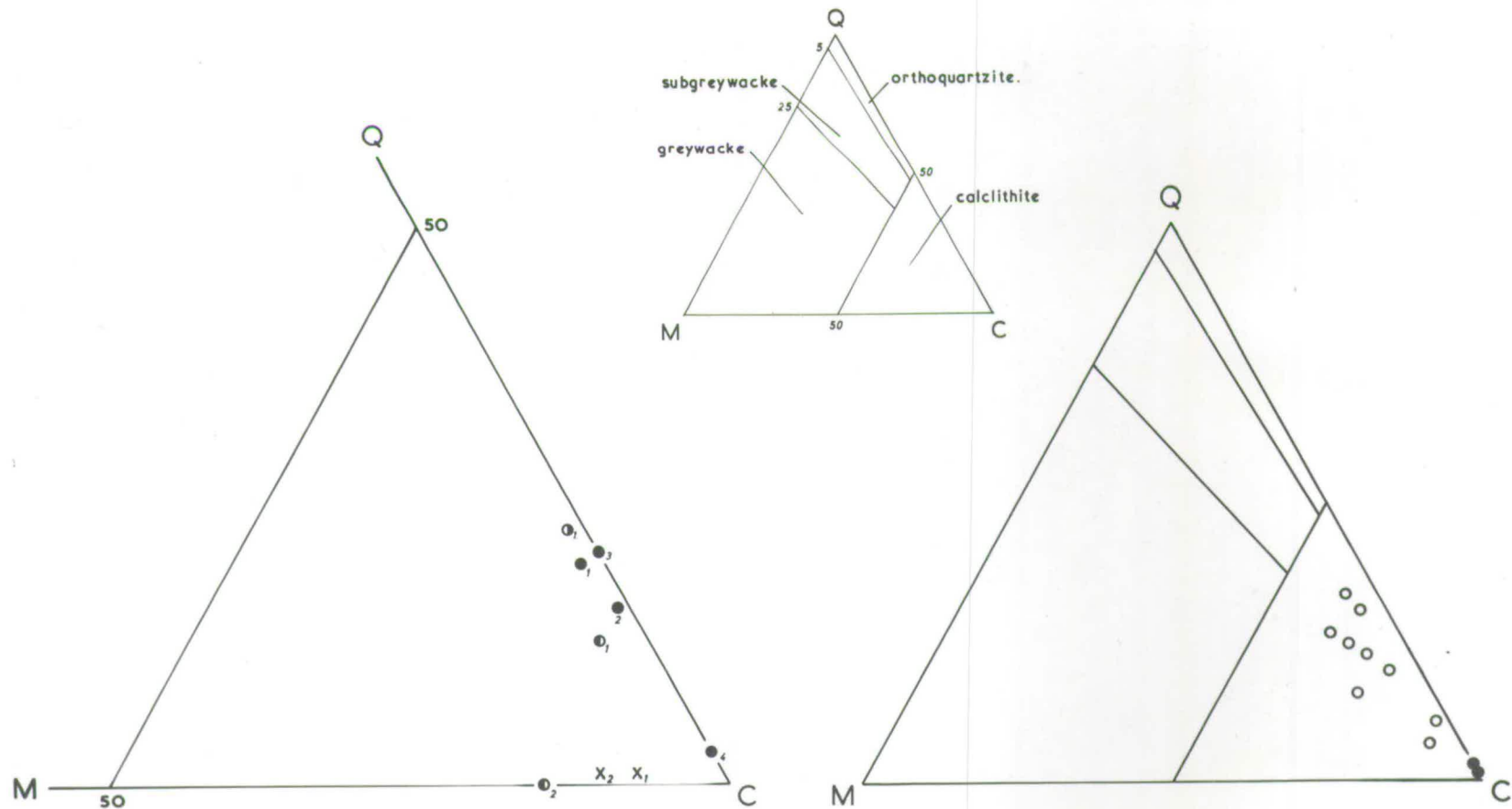


FIG. 70. Rock compositions plotted on the Q - C - M diagram of Folk (1964). Q = Qtz. + o'quartzite + chert; C = all carbonate RF's; M = Metamorphic RF's + stretched metaquartzite.

All symbols as in FIG. 71.

On the left are the sand grade rocks, and on the right are the breccias.

breccia deposits. Others have a relatively limited vertical spread - e.g. the shales and siltstones (presumably Lias) tend to be concentrated in the Lower Breccia, but their small proportions (0 - 10% of total rock fragments) makes their influence on the total rock composition but small. Similarly, the fragments of metamorphic schist, which first appear near to the top of the flysch facies of the Lower Breccia, are distinctive members of the upper half of the sequence, but they still make up only 0 - 15% of the total rock fragments. Apart from these relatively minor variations, carbonate clasts tend to dominate.

The bulk of the sand grade and coarser rocks fall into the calcilithite class of Folk (1964) (FIG. 70). There are however the following exceptions:-

1. The thin graded subgreywackes in the Upper Shales.
2. The lithic pelbiomicrites which often form the uppermost parts of breccia beds in the Upper Breccia Formation, or which occur as gravelly calcareous mudstones in the Upper Breccia, and Upper Shales.

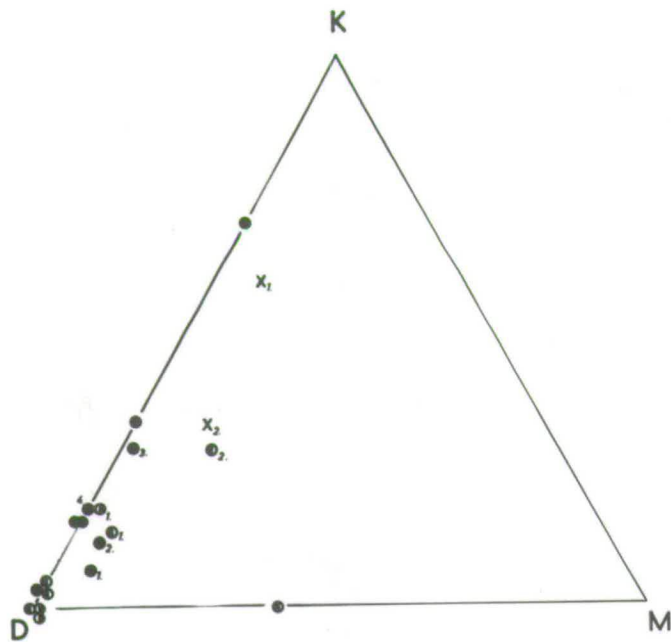
However, if the composition of the Upper Breccia breccias is decided on the basis of clast composition, disregarding the sand grains in the matrix and finer breccia tops, then they too, must be considered calcilithites (FIG. 70).

Because of the dominant role of carbonate rock fragments, there is little marked variation in rock fragment proportions from bottom to top of the sequence. If the rock fragments are divided into broad categories according to age of the presumed

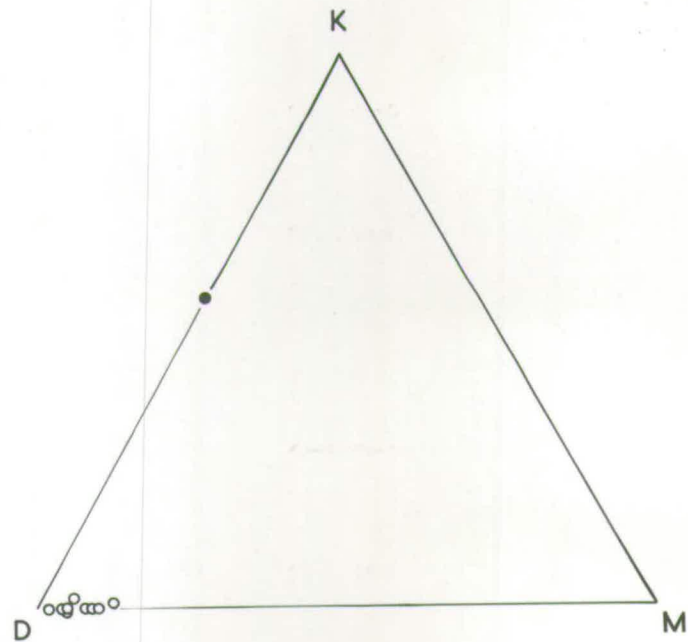
source rocks, compositions may be expressed in terms of the following three end-members (FIG. 71):-

- K calcareous rock fragments + shales - presumed to be Liassic material.
- D dolomitic rock fragments + orthoquartzites + sandstones - presumed to be principally Triassic material.
- M Metamorphic rock fragments + metaquartzite + volcanic rock fragments. - presumed pre-Triassic material.

This shows the slight migration of some Upper Breccia samples towards the M-pole. However, the relative proportions of calcareous and dolomitic rock fragments would appear to be more complex than has been suggested. If the clasts in the breccias are examined, it is clear that the breccias of the Upper Breccia Formation contain few limestone clasts (FIG. 72). The calcareous clasts in the finer grained rocks of the Upper Breccia (and similar 'Upper Breccia-type' rocks in the Upper Shales) are usually micrite pellets, ooids, or fossil fragments. The lack of limestones containing such material among the pebbles and cobbles of the breccias suggests that this fine material may have been derived from an intraformational source. The great thicknesses of micrite limestone in the Upper Breccia Formation are further evidence that this source has favoured supply of fine rather than coarse material. In some samples, the pellets etc. can be clearly distinguished from other



- - Lower Breccia Calclithites.
 1. Praz de Lys. (4 samples).
 2. Roc d'Enfer. (5).
 3. Avoréaz (4).
 4. Pont des Gets - Avonnez (4).
 - - Upper Shales Calclithites.
 1. Praz de Lys. (5).
 - - Upper Breccia 1 + 2, Avoreaz (calclithites - 4)
 - x - Upper Breccia, breccia tops - Praz de Lys (4).
- unnumbered symbols - individual samples.



- - Lower Breccia (field analysis)
 - - Upper Breccia (field analyses)
- All breccias.

FIG. 7L. Compositions of the rocks interms of the three main sources.

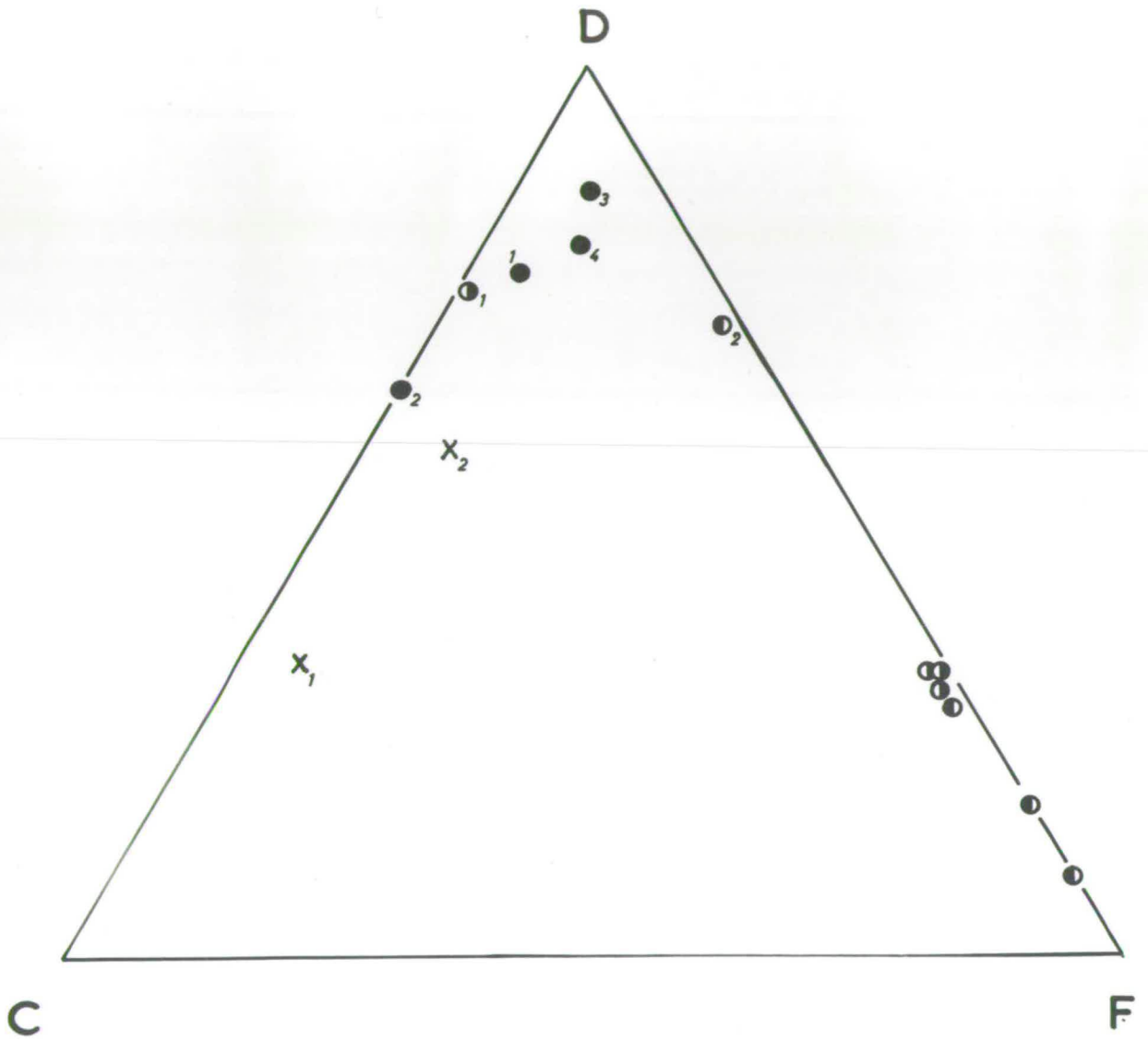


FIG. 72. D - C - F diagram to show contribution of penecontemporaneous carbonate material.

calcareous material. If these are plotted on a D - C - F diagram (D = dolomitic rock fragments; C = calcareous rock fragments; F = penecontemporaneous material such as pellets, cooids, and fossils and fossil fragments) they tend to fall near to the F-pole of the chart (FIG. 72). Near to the tops of breccia beds in the Upper Breccia, where the material is largely sandy and silty, it is impossible to say with certainty that the detrital calcareous grains had a biogenic source, so they may plot away from the F-pole.

The Upper Shales Formation has a distinct enrichment in silica, with the occurrence of beds of silty siliceous mudstones, and subgreywacke rocks. Inspection of the Q - C - M diagram reveals that this enrichment extends also to the calclithites (FIG. 70). The silica content of these calclithites is almost entirely in the form of monocrystalline quartz, and as such, may have been derived from either the Triassic quartzites and sandstones, or from the pre-Triassic schists.

Shale fragments, which may form up to 10% of rock fragments in the Lower Breccia beds, but often form much less, are also found in the Upper Breccia, where they may constitute as much as 3% of rock fragment types. Taken alone, they are not really good indicators of stratigraphic position.

Schroeder (1939), has reported clasts of 'veined eruptive rock' from the breccias of the Upper Breccia. Current studies have revealed traces of brown very finely crystalline, siliceous rock fragments, which presumably had a (Permian) volcanic origin.

2. Textural characteristics.

The major part of the succession is composed of immature-submature (in the sense of Folk 1964) rocks, the exceptions being the finest grained rocks such as the shales and mudstones of the Upper Shales, and the micrite limestones of the Upper Breccia.

a) Clast shape.

Studies of the breccias in both Upper and Lower Breccia Formations, have shown that clasts are but poorly rounded (FIGS. 12 and 66). Inspection of fine-grained rocks reveals a similar degree of wear on smaller clasts, though corrosion and stylolitization can both affect grain shape. There are two exceptions to the poorly rounded state:-

1. Oolites and pellets and some fragments, which are believed to have had an intraformational origin.
2. Some quartz and feldspar grains which have probably been recycled from Triassic sandstones.

b) Sorting of the clasts.

In the Lower Breccia, the breccias, although they do not have a fine matrix, show a wide range of clast sizes. Only in their cross-stratified tops do they sometimes have better sorting, but even then they are only moderately sorted (sorting classification of Folk 1964) as was found for the analysis in FIG. 8. The other curve in FIG. 8, which represents the breccia which was analysed for clast size grading, and is thus representative of the whole bed, has an

Inclusive Graphic Standard Deviation (σ_I) (Folk 1964) of 1.01, i.e. the lowermost part of the 'poorly sorted' class of Folk (1964).

The calcilithites in the Lower Breccia are also poorly sorted. Inspection of FIGS. 38 and 43 shows that the laminated parts of some beds have around 10% - 20% of fine matrix (less than 6ϕ in size). Calculation of σ_I shows that most of the samples fall into the 'poorly sorted' class of Folk (one is 'very poorly' sorted, and one is 'moderately sorted'). In the Upper Shales, apart from the finest grained rocks, all rocks show similar sorting characteristics to their counterparts in the Upper and Lower Breccia Formations.

In the Upper Breccia, the breccias may contain up to 40% muddy matrix, (FIG. 59), and even the clast size distributions show a wide spread (FIG. 64, curve A). The calcilithites and gravelly calcareous mudstones are likewise poorly sorted. Only the micrite limestones are texturally homogenous.

VI. SUMMARY AND CONCLUSIONS.

The sediment pile from the Lower Breccia/Lower Shales through to the Upper Breccia represents a phase of coarse, predominantly carbonate deposition in the history of the original depositional basin of the Nappe de la Breche sedimentary rocks (FIG. 73).

The Lower Breccia was initiated by the deposition of thick, mud-free, gravelly, polygenic breccias from inertia flows. On the basis of thickness variations, of both single beds and the total breccia pile, facies changes, and variation in maximum phenoclast size, an origin from the south-west, west, north-west, north region is favoured. The thickness variations of the breccia facies suggest that dispersal may have been in the form of at least two large submarine fans. Although the breccias were introduced as rock flows, the action of fairly strong indigenous bottom currents produced dune cross-stratification, and parallel stratification at the topmost parts of many breccias. Bottom currents are not considered to have played a significant part in the introduction of the breccias because of the very coarse nature of the main parts of the breccia beds, and the upper limit to clast sizes which occur in the stratified parts.

The breccia phenoclasts are mostly limestones, shales, siltstones, and dolomites, of presumed Liassic and Triassic age.

The breccia facies passes laterally and upwards into the flysch facies of the Lower Breccia. This consists of a sequence of graded calcilithites with some breccias and

WNW

ESE

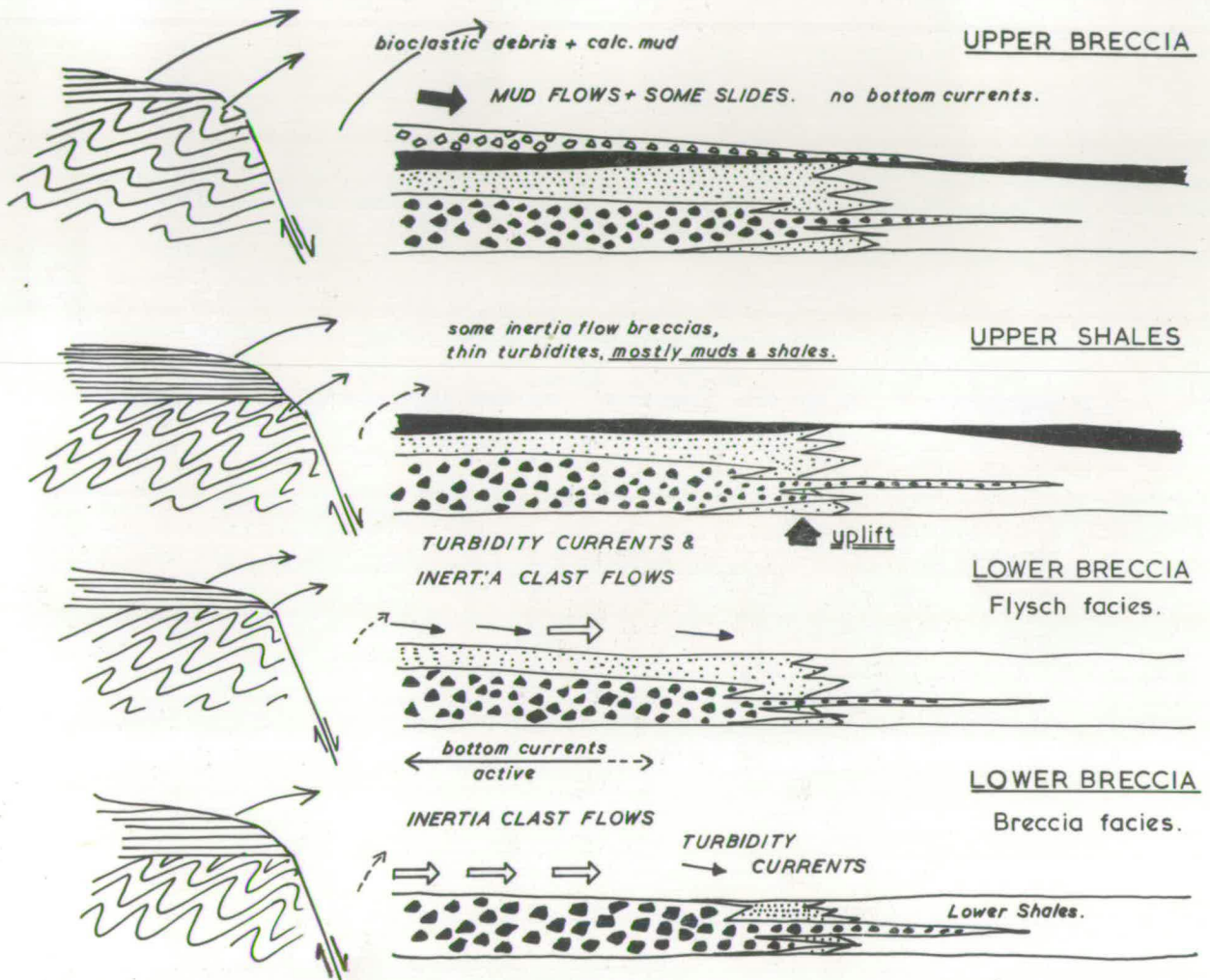


FIG. 73. Sedimentary history of the original breccia basin.

calcareous silty pelites. The graded beds contain structures indicative of deposition from turbidity currents, and sometimes have a lowermost dune division. Formation of a dune division is probably most dependent on the availability of material of critical grain size in appropriate quantities. It is probably a near-source structure. The breccias in the flysch facies differ from those in the breccia facies by not having cross-stratified upper portions - this, coupled with the widespread occurrence of sand-grade beds, indicates that during deposition of the flysch facies, strong indigenous bottom currents were no longer operating.

A facies change can be traced from the breccia facies of the Lower Breccia, through the flysch facies of the Lower Breccia, to the Lower Shales Formation, so these were at least partly contemporaneous.

A lateral passage from the flysch facies of the Lower Breccia to so-called Upper Shales has also been demonstrated. The Upper Shales (s.s.) do not pass laterally to the Lower Breccia or Upper Breccia. They are characterized by a more siliceous composition with red and green silty mudstones, minor amounts of subgreywacke, and more quartz in the calcclithites. There is also a general fining of the rocks, and although some breccias do occur, they are scarce. The breccias in the Upper Shales are of the Lower Breccia textural type, and occur right to the top of the formation. Both the upper and lower boundaries are transitional.

At the top of the flysch facies of the Lower Breccia, and in the Upper Shales, metamorphic rock fragments appear in the rocks, indicating that erosion in the source area has penetrated the sedimentary cover.

Directional structures are lacking in the Upper Shales, and thickness variations show an unusual pattern, but it is most likely that the sediment originated to the west and/or north.

In the Upper Breccia mud flows from the north-west produced a south-easterly thinning wedge of muddy breccias. These breccias are commonly graded, but they are not generally so coarse as those in the Lower Breccia. Although they were usually the products of mud flows, partially cohesive behaviour indicates the operation of slides in some cases. The lime mud which is interbedded with the breccias shows that no bottom currents operated at this site during Upper Breccia times.

Trumpy (1955) suggested that the sediments of the Breccia Nappe originally accumulated along the tectonically active boundary between the Brianconnais Cordillera and the Piemont Trough during Jurassic and Cretaceous times.

The present study has revealed a sedimentation pattern which is compatible with such a setting. The evidence indicates a nearby source for the breccias, with rapid erosion and deposition of the material. The breccia formations are both composed of polygenic breccias, but the breccias in each formation contrast strongly in textural features. This is a

result of mode of formation - until the beginning of Upper Breccia times, only boulder/cobble mud-free breccias, the results of inertia clast flows, were deposited, but at the base of the Upper Breccia Formation, breccias with considerable mud matrix appear, and these are the results of mud flows. Graded calcilithite beds, deposited from turbidity currents, are interbedded with the inertia flow breccias especially. The finer grained parts of the succession are the Lower Shales Formation, which is a partial lateral equivalent of the Lower Breccia, and the Upper Shales Formation, which includes red and green mudstones. The latter is more strictly defined in the present study than in the reports of Schroeder (1939), and Arbenz (1947), and shows no great lateral transition to the Lower Breccia, although there is a rapid vertical transition. The upper limit of the Upper Shales shows a rapid change to the Upper Breccia but there is no lateral change.

The rock fragment assemblages are not diverse, and reveal erosion of an area of predominantly carbonate rocks. Other rock fragment types found in the breccias - shales and metamorphic schists - comprise only minor proportions of the whole rock fragment assemblage.

Such a pile of texturally and mineralogically immature sedimentary rocks of calcilithite composition, could only have accumulated by the rapid erosion of a nearby landmass, composed mainly of carbonate rocks, which was undergoing extensive uplift during Jurassic and Cretaceous times. The limitations as to the environment imposed by the

characteristics and age of these rocks, make the northern margin of the Piemont Trough the most likely original site of the nappe.

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A C K N O W L E D G E M E N T S .

The research was carried out at the Grant Institute of Geology, University of Edinburgh (1966-68), and the Department of Geology, University of St. Andrews (1968-69), during the tenure of an N.E.R.C. Research Studentship Award, which is gratefully acknowledged.

I am indebted to Professor A. Lombard, Geology Department, University of Geneva, Switzerland, for introducing me to the geology of the Nappe de la Breche, and for the use of library facilities at the University of Geneva.

I should also like to thank M. Jean Zenoni, Scieur, Pont des Gets, Taninges, and his family, for their hospitality and friendship during my field seasons in the French Alps.

For the provision of research facilities at the Grant Institute of Geology, and the Department of Geology, St. Andrews, I am grateful to Professor F.H. Stewart, and Professor E.K. Walton.

Technical assistance was provided by Mr. S. Bateman, Mr. N. Spittal, and Mr. G. Tasker, all of the Geology Department, St. Andrews University. Photographic work for the thesis was done by Mr. N. Mackie, Department of Geology, University of St. Andrews. Mrs. J. Galloway, Department of Geology, University of St. Andrews, typed the script.

Finally, my thanks go to Professor E.K. Walton, University of St. Andrews, who supervised the study, and whose helpful discussion and criticism gave me encouragement at all stages of the research.

APPENDIX 1.

Lithological analyses.

Analyses of rocks in thin section were made using a Swift Point Counter. Twelve single samples were analysed, and thirty-two samples were analysed to give nine locality analyses. In the former case 700-1900 points were counted per thin section, and in the latter, at least 200 points per thin section.

The following results were obtained:-

LOCALITY SAMPLES

	DRF	CRF	MRF	VRF	SRF	Q(met)	Q	Bio.	Matrix
<u>L. Breccia</u>									
Praz de Lys (4)	64	6	1	-	t	3	15	5	5
Pont des Gets (4)	69	16	-	-	t	-	3	4	8
Avoreaz (4)	27	15	-	-	1	-	11	-	46*
Foron d'en bas (5)	61	8	1	1	2	-	14	7	5
* fine grained samples.									

<u>U. Shales.</u>									
Praz de Lys	56	18	-	-	1	1	24	t	t*
* much of matrix is recrystallized.									

<u>U. Breccia</u>									
Praz de Lys (2) (breccia tops)	27	51	6	-	-	-	1	5	10
Praz de Lys (4) (breccia tops)	24	15	5	2	-	t	t	3	52
Avoreaz (2) calclithites log XVI	28	14	6	-	-	-	-	-	50
Avoreaz (2) calclithites log XXV	59	9	4	-	-	3	10	-	15

SINGLE SAMPLES.

		DRF.	CRF.	MRF.	VRF.	SRF.	Q(met)	Q	Bio.	Mat.
II	43	97	-	-	-	3	-	t	-	*
X	1	30	70	-	-	-	-	-	-	*
X	B3	84	6	-	-	10	-	-	-	*
XIII	7	84	6	-	-	10	-	-	-	*
XIII	20	95	-	-	-	5	-	-	-	*
XIII	21	66	27	-	-	7	-	-	-	*
VI	1	16	-	t	-	t	t	t	83	*
VIII	6	65	2	t	-	-	t	4	29	*
XIV	4	8	-	-	-	1	t	t	83	*
IX	6	37	-	24	t	-	2	5	32	*
IX	18	30	-	t	t	t	t	4	64	*
IX	20	62	-	1	T	3	1	3	30	*

Single samples. 700-1900 points counted per section.

In all cases the matrix (if any) had recrystallized to spar.

The first six are from the L. Breccia

VI 1, and XIV 4 are breccia tops in the U. Breccia

and the others are U. Shales samples - mainly gravelly calcareous mudstones.

t = trace

* matrix considerably recrystallized.

DRF - dolomitic rock fragments
 CRF - calcareous rock fragments
 MRF - metamorphic rock fragments
 SRF - sedimentary rock fragments, excluding carbonates.
 Q(met) - metamorphic quartz
 Q - quartz
 Bio. - bioclastic material
 Matrix - fine grained clay or carbonate matrix.

Analyses of the coarse-grained rocks.

The breccias were analysed in the field by point-counting using a suitably sized orthogonal grid. The spacing depended on grain-size of the particular sample. The results are as follows:-

	<u>Calcareous + Dolomitic Rock Fragments.</u>	<u>Metamorphic Rock Fragments.</u>	<u>Siliceous Rock Fragments.</u>
1.	72	12	16
2.	66	9	25
3.	62	11	27
4.	61	5	34
5.	65	4	31
6.	75	5	20
7.	70	7	23
8.	86	2	11
9.	88	5	7
10.	90	0	10

1 - 9 Upper Breccia breccias.

10 Lower Breccia breccias.

APPENDIX 2.

Bartlett's test for the homogeneity of variances.

In analysis of variance problems it is necessary to assume that a number of population variances are equal. If there is reason to doubt that this is the case the following hypothesis may be tested

$$H_0 : \sigma_1^2 = \sigma_2^2 = \sigma_3^2 = \dots = \sigma_n^2$$

H_1 : at least two variances are different.

Under the assumptions that (a) n random samples are drawn from n populations and (b) then populations are normal, the statistic

$$\frac{2.3026}{C} (k - 1) \left[n \log S_p^2 - \sum_{j=1}^n \log S_j^2 \right]$$

is approximately distributed as chi-square with $n - 1$ degrees of freedom if H_0 is true. Here $s_1^2, s_2^2, s_3^2, \dots, s_n^2$ are the n sample variances.

Each sample has k items, and the total number of items is N.

Also,

$$S_p^2 = \frac{\sum_{j=1}^n S_j^2}{n}$$

and,

$$C = 1 + \frac{1}{3(n-1)(k-1)} \left(n - \frac{1}{n} \right)$$

The more the s_j^2 differ from one another, the larger this statistic becomes.

If the s_j^2 are all nearly the same, then the statistic is small.

Hence H_0 is rejected only for large values.

Results for the graded breccia in the Upper Breccia Formation.

For this bed the values are:-

$$n = 56 \quad k = 5 \quad N = 280$$
$$S_p^2 = \frac{\sum_{j=1}^n S_j^2}{n} = 4.332, \quad n \log S_p^2 = 35.655$$

$$\text{and } \sum_{j=1}^n \log S_j^2 = 21.9$$

$$n \log S_p^2 - \sum_{j=1}^n \log S_j^2 = 13.755$$

$$C = 1 + \frac{1}{3(n-1)(k-1)} \left(n - \frac{1}{n} \right)$$
$$= 1 + \frac{1}{3 \times 55 \times 4} \left(56 - \frac{1}{56} \right) = 1.0848$$

therefore, the value of the statistic is

$$\frac{2.3026}{1.0848} \times 4 \times 13.755 = 116.81$$

Consultation of chi-square table with 55 degrees of freedom indicates that the hypothesis of equal variances should be rejected.

APPENDIX 3.

Field work was carried out in 1966 (Sept.), 1967, (May and June) and 1968 (June and July). Most of the area is below 2000 m and is reasonably well exposed. Access by car to many parts of the area is good and the road network is improving. Snow may prevent access until the end of May.

The area studied is covered by Carte de France au 50.000^e (Type 1922), SAMOENS - PAS DE MORGINS, Feuille XXXV-XXXVI-29.

The following localities are significant with respect to the present study:

LOCALITY

Crest from Chalet de Roi to
Pointe de la Couenasse (Praz de
Lys).

FEATURES

Down sequence (east-west) transition from U. Breccia to U. Shales. Here the contrast between the muddy U. Breccia-type breccias and the underlying L. Breccia-type breccia, at the top of the U. Shales is well shown. Following the crest to the west, all the lithologies of the U. Shales are exposed. There is then a passage to the flysch facies of the L. Breccia. The features of the latter are best seen on the southern flank of this crest accessible from below - gravel waves and load

Pic de Marcelly

(Praz de Lys)

Marcelly (to the south of
Pic de Marcelly, on the
Taninges-Rond road.

Along Route Nationale 202
from Taninges to Pont des Gets.

Road from Le Mont (near
Avonnoz) to la Biolle.

Large cirque to north-east of
Pic de Marcelly.

East and north of Lac de Roi
(Praz de Lys)

structures in the breccias;
chaotic-type breccias;
grading in the breccias; sole
markings on the breccias;
dune structures in the
calclithites; grading,
parallel- and cross-laminat-
ion, in the calclithites;
the calclithite-pelite
lithology - all these are
well exposed on this slope.

At and near to the summit are
thick breccias of the Lower
Breccia, breccia facies.

Thick breccias of the Lower
Breccia, breccia facies.

Lower Shales at Avonnoz, then
northwards - flysch facies of
L. Breccia.

Flysch facies of Lower Breccia.

Breccias of breccia facies.

Lower Breccia showing pebble
lineation; α and β - cross-
stratification types; grading.

Upper Breccia. Breccias with
excellent grading, deformed

matrix lumps, fine breccia

Where road from Pont des Gets enters Praz de Lys.

La Biolle - les Mais.

Sur les Chables

(access from Verchaix or Samoëns).

Montagne d'Uble, north-west of Chalets d'Uble.

Montagne d'Uble north facing slope.

Gorge of le Boutigny (between les Cotes and Bonnavaz, access from Pont des Gets - Praz de Lys road).

Roc d'Enfer, south facing slopes above le Foron.

Roc de Tavaneuse (access from Abondance).

Les Lindarets (access from Morzine and Montriond).

U. Breccia. Thick breccia bed with lumps of matrix.

Extremely thin U. Breccia and U. Shales Formation.

Lower Shales Formation with some breccias. Roadside exposures.

U. Breccia. Inclusion of breccia slabs in micrite limestone.

U. Shales and U. Breccia.

U. Shales U. Breccia transition.

U. Breccia: thick, graded, breccias with erosive bases. Thick breccia facies of Lower Breccia. Flysch facies well-exposed also. Both U. Shales and U. Breccia are exposed but access is difficult.

Shows U. Breccia overlying L. Breccia without the U. Shales between. The contact is marked by the site of the village.

Sandy lenses occur near to the base of one L. Breccia breccia.

Les Lindarets - Col de Chésery.

Col de Chésery.

Les Lindarets - Avoréaz.

Avoréaz.

The flysch facies of the L. Breccia, on the road below Les Lindarets shows sole markings, grading, and gravel bars.

Sporadic exposures of U. Breccia breccias with matrix lumps.

U. Shales.

L. Breccia: mostly breccia beds Grading, cross-stratification.

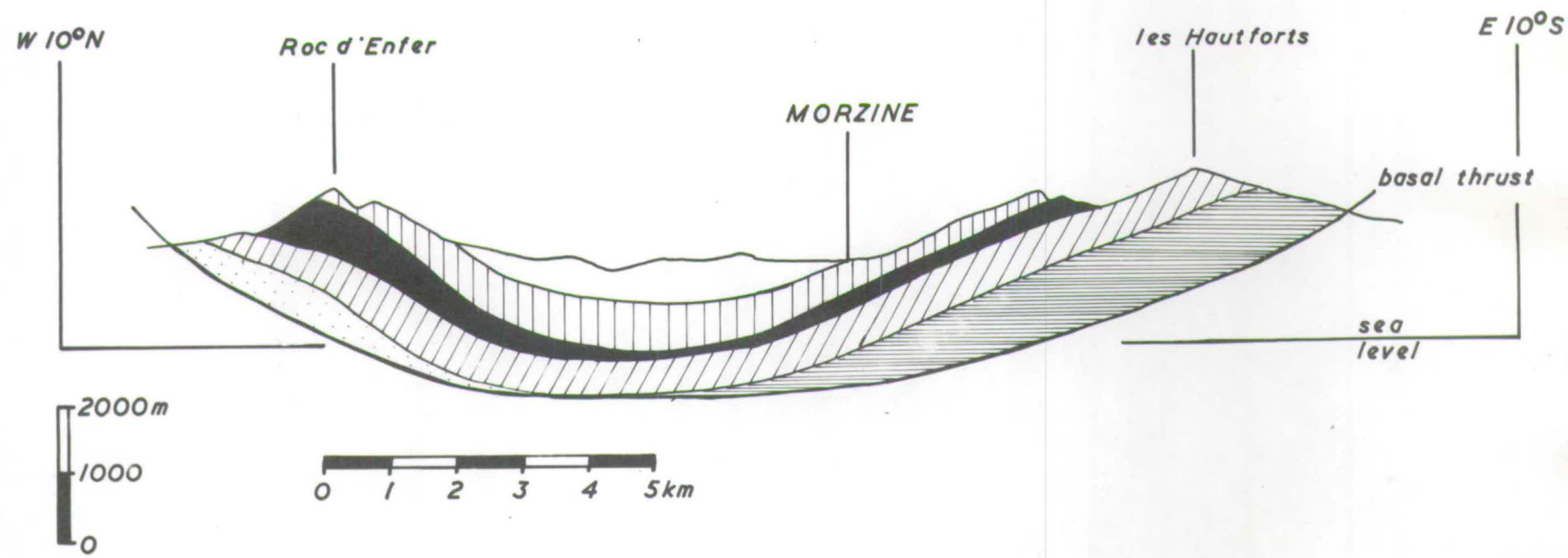
U. Breccia: some thick breccia beds; usually graded, matrix lumps etc.

U. Shales: most lithologies represented. No thick breccias.

L. Breccia: Flysch facies - grading, convolutions, etc.

Soft mud clasts in breccias.

Breccia facies - cross-stratification at tops of breccia beds.



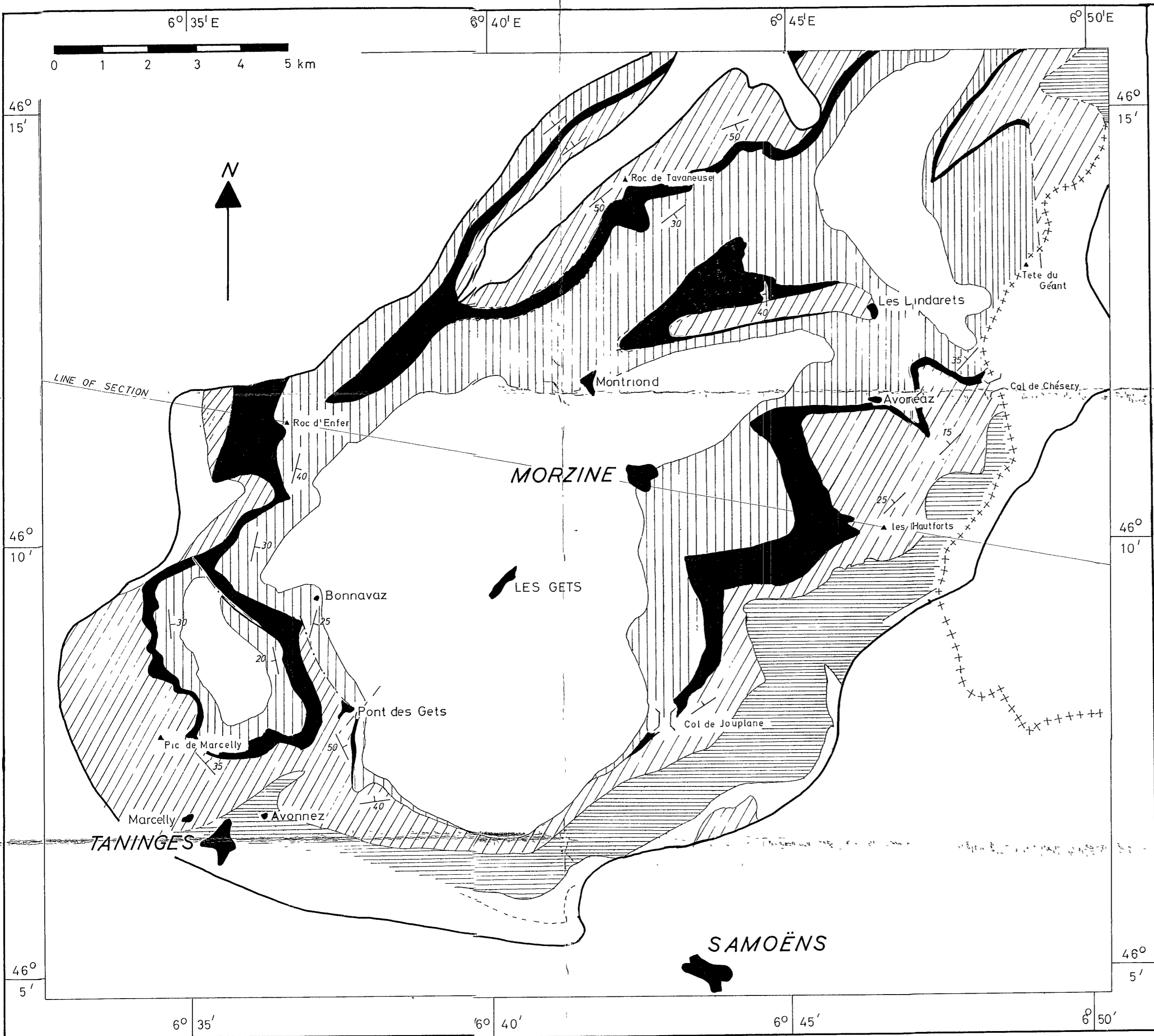
GRAPHIC LOG I
LOWER BRECCIA
BRECCIA FACIES
COL DE CHESERY

Bed No.	Bed Thickness (cm.)	TEXTURE					Graded Thin bedded	Parallel laminated	Cross laminated
		Boulder	Cobble	Pebble	Granule	Sand			
19	300								
18	700								
17	400								

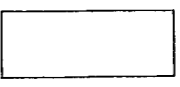
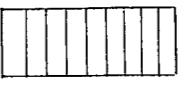

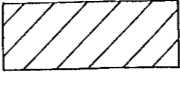
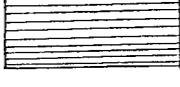
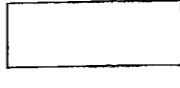
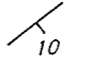
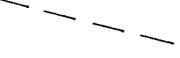

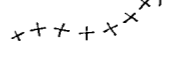
No.	Th.	B	C	P	G	S	P	G	T	P	C
17	400										
16	100										
15	200										
14	50										
13	100										
12	100										
11	40										
10	40										
9	200										
8	200										
7	300										
6	250										
5	100										

No.	Th.	B	C	P	G	S	P	G	T	P	C
4	300										
3	500										
2	800										
1	300										

At this locality individual breccia beds do not show maximum thickness development but the proportions of different lithologies are typical.



THE GEOLOGY OF THE NAPPE
DE LA BRECHE.

-  *post-Upper Breccia*
-  *Upper Breccia*
-  *Upper Shales*
-  *Lower Breccia*
-  *Lower Shales*
-  *pre - Lower Shales*
-  *dip and strike of beds*
-  *fault*
-  *basal thrust plane*
-  *frontier*

The map is modified and simplified after Lugeon (1896), Schroeder (1939), and Chessex (1959).

ABSTRACT OF THESIS

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Degree Doctor of Philosophy Date October, 1969

Title of Thesis Sedimentary Studies in the Nappe de la Breche, French Prealps.

The sequence of rocks studied* is divided into the following units on the basis of texture and mineralogy:- (1) Lower Breccia Formation (Breche Inferieure) - breccia facies; (2) Lower Breccia Formation - flysch facies; (3) Upper Shales (Schistes Ardoisiers) Formation; (4) Upper Breccia (Breche Superieure) Formation.

Variation in thickness of the breccia facies of the Lower Breccias, thickness of individual beds, proportion of breccia in the succession, and maximum phenoclast size indicate a source area to the north and west. The breccia facies of the Lower Breccia passes in a south-easterly direction to the flysch facies and then into the Lower Shales (Schistes Inferieurs) Formation. There is also an upward passage from the Lower Breccia, breccia facies to the Lower Breccia flysch facies. Breccias in the breccia facies are believed to have been transported as inertia clast flows, and after deposition their uppermost parts were reworked by bottom currents. Breccias occur in the flysch facies but sand-grade beds are more common. The sand-grade beds (calclithites) are commonly graded and were deposited by turbidity currents. The calclithite turbidites are often coarse and sometimes contain dune structures. These dunes are similar to those in the limestone member of the Whitehouse Formation (Ordovician) at Girvan, Scotland. Their formation is believed to depend principally on the availability of granule-pebble material, and they are indicative of a proximal turbidite environment. Also found in the turbidites is a repetition of several divisions of parallel lamination, and current-ripple lamination. This feature, which also occurs in the limestone member of the Whitehouse Formation at Girvan, indicates that internal structures in turbidites do not always represent a simple decrease in flow power. Grain size distribution in, and rate of deposition from, a turbidity current are cited as important factors in determining the final sequence of internal structures in a turbidite. The influence of rate of deposition on development of a preferred orientation of elongate grains is demonstrated with reference to two graded calclithite beds.

The flysch facies of the Lower Breccia Formation passes upwards into the Upper Shales Formation, where breccias are scarce but still of the Lower Breccia-type. Here, shales and mudstones predominate, and the thickness variations suggest existence of a south-west to north-east rise in the centre of the basin. At some parts of this rise, there was no deposition of the Upper Shales.

With cessation of deposition of the Upper Shales, coarse breccias appeared again. These breccias contrast strongly with those of the Lower Breccia. They have up to 40% calcareous mud matrix, and are well-graded. A mud flow origin is suggested. Occasional irregular distribution of matrix, 'clouds' of fine breccia in coarse, and slabs of breccia in the interbedded limestones indicate cohesive behaviour in some cases. The source for these breccias was to the north and north-west.

Palaeocurrent indicators are few. The bottom currents which reworked parts of the Lower Breccia, breccia facies - breccias were variable in direction but fitted into the submarine fan environment which is envisaged for these rocks. In the flysch facies of the Lower Breccia a few sole markings and dune structures indicate a more or less west to east dispersal, while directions obtained from current ripple cross lamination show wide variation, particularly in the

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*(Jurassic - Cretaceous)

thinner beds. This variation is interpreted as a result of deposition from thin turbidity flows passing over an irregular bottom, but some reworking by indigenous currents cannot be ruled out. There was no bottom current action during deposition of the Upper Breccia Formation.

The lithologies throughout the sequence reveal a source area of predominantly carbonate rocks. The appearance of metamorphic rock fragments at the top of the Lower Breccia indicate penetration of the sedimentary cover, but their relatively small proportion shows that exposure of metamorphic terrain was not extensive. During Upper Breccia times a significant contribution was made by the supply of bioclastic material and lime mud presumably from the littoral region. Rounding of clasts is generally poor and indicates no extensive working of the material by currents.

The sediments were deposited in a near-source environment by inertia clast flows, turbidity flows, mud flows, and slides. Some reworking by bottom currents took place in the lower part of the succession, but introduction of the material by bottom currents is not considered likely. The source area was undergoing uplift. Erosion, transport, and deposition were rapid. A likely original site of deposition is about 100 km to the south, at the northern margin of the Piemont Trough, during Jurassic and Cretaceous times (Trümpy 1955), with the adjacent Briançonnais Cordillera providing a nearby source area. This suggestion is endorsed by the present author, in light of the results of this study.