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Application of turbidite sedimentology to determination of thrust fault displacements in the Carolina Slate Belt

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Abstract—Discontinuities in the lateral variations of grain size, bed thickness and internal sedimentary structures of 'classic turbidites' are used to calibrate thrust fault displacements in the Carolina Slate Belt. The Ugly Creek Thrust, just east of Albemarle, North Carolina, has been determined to have a displacement of 11.7–19.6 km, while the Uwharrie Thrust in the same area has a displacement of 19.6–29.5 km. The method relies on the predictability of lateral change in a down-paleocurrent direction of sedimentological parameters. Values of the various parameters from opposite sides of the thrust fault are cross-plotted against their lateral down-current distance from a common reference point or base line. Data from one side of the fault are shifted relative to that of the other along the lateral distance axis so as to construct by eye a curve that mimics a predetermined curve form for lateral change of the parameter. The amount of shifting necessary to achieve this is equal to the apparent thrust displacement in the down-current direction. This is then trigonometrically related to the actual thrust displacement.

INTRODUCTION

A COMMON characteristic of sedimentary rocks is that depositional features such as bed thickness and grain size vary spatially in a somewhat systematic way. Thrust faults that offset a given formation will thus distort the pattern of the depositional features. The thrust offset can be calibrated if the depositional pattern can be reconstructed (Dott 1934, Kay 1945, Rowley 1982). Crittenden (1961) utilized unit thickness to calibrate displacements across the Charleston–Nebo–Bannock Thrust in northeastern Utah. The displacement was estimated from the apparent discontinuity in mapped isopachs across the fault (Crittenden 1961, figs. 335.1, 335.2 and 335.3). In our initial studies in the Carolina Slate Belt (Huntsman & Dockal 1985, 1986, Dockal & Huntsman 1986) we attempted to calibrate fault displacements by using trend surface maps of various sedimentologic parameters in much the same manner that Crittenden (1961) used the isopach maps. As an improvement on this method we suggest the elimination of the trend surface maps and in their place using cross-plots of the various parameters vs lateral distance from a 'base line' which is oriented normal to the average paleocurrent trend of the area. From the cross-plots the apparent tectonic shift of the strata in the down-paleocurrent direction is determined. This is then trigonometrically related to the actual thrusting distance.

This paper illustrates this method of calibration of thrust displacement where it has been successfully utilized in the weakly metamorphosed turbidites of the Carolina Slate Belt near Albemarle, North Carolina (Fig. 1). Individual thrusts in the slate belt, as interpreted here, have resulted in lateral displacements of 12–29 km.

GEOLOGIC SETTING

The Carolina Slate Belt, a major lithotectonic element of the North Carolina segment of the southern Appala-

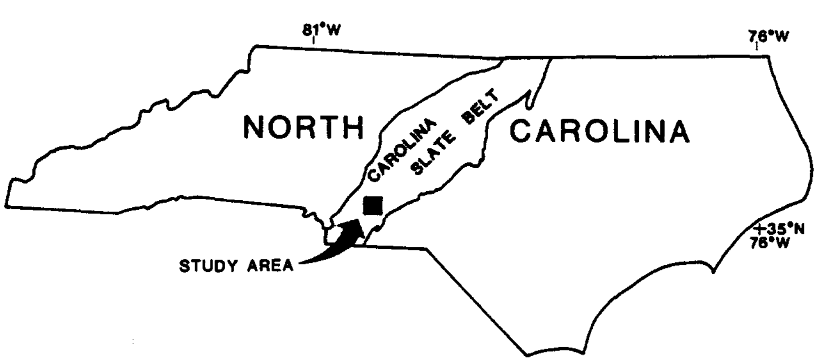


Fig. 1. Location map. The central area represents the Carolina Slate Belt.

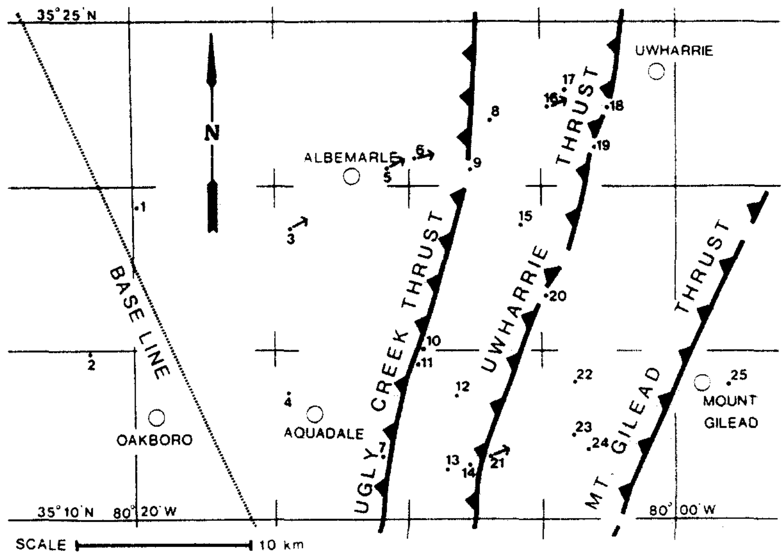


Fig. 2. Map of the study area showing the location of the thrust faults, outcrops used in the study and the 'base line'. Numbers correspond to the outcrop numbers in Table 3. Arrows denote the location and determined direction of paleocurrent data. Thrust fault trends have been generalized and in part projected under the Uwharrie volcanics.

chians, is a poorly exposed and weakly metamorphosed Proterozoic Z to Middle Cambrian volcano-sedimentary sequence that has been subjected to Taconic to Acadian deformation (Conley & Bain 1965, Stromquist & Sundelius 1969, Seiders & Wright 1977, Feiss 1982, 1985, Green *et al.* 1982, Gibson & Teeter 1984, Milton 1984, Schmidt 1985). It has been suggested that the Carolina Slate Belt is an Avalonian terrain (Feiss 1984, 1985). The volcano-sedimentary sequence is now generally considered to have been the product of an active continental margin or volcanic island arc (Butler & Ragland 1969, Glover 1973, Feiss 1985, Schmidt 1985).

Three NW-dipping thrust faults have been mapped to date in the Albemarle segment of the Carolina Slate Belt (Fig. 2). Fault-related folds of the Ugly Creek thrust sheet are open to close, asymmetrical concentric folds plunging gently NE with interlimb angles between 85° and 140°. Concentric folds with interlimb angles ranging from 85° to 40° or less dominate fold styles in the Uwharrie and Mount Gilead thrust sheets. Southeastern limbs of the folds are slightly steeper than northwestern limbs. Thrust transport direction is constrained towards the ESE by:

(a) observed flat–ramp–flat geometries in outcrop exposures;

(b) vergence of folds and small and widely-spaced kink bands and discrete zones of crenulation; and,

(c) highly-weathered slickensided surfaces at several localities.

Because all of the fault splays and flat–ramp–flat geometries root downward into the Tillery Formation, we interpret a regional detachment surface at this stratigraphic level.

The most prevalent cleavage in the Ugly Creek thrust sheet is a fanning axial-planar cleavage with rough to smooth domainal shapes and sinuous to anastomosing patterns. A second cleavage is smooth to planar in shape. This cleavage occurs within the Uwharrie thrust sheet and the eastern parts of the Ugly Creek thrust sheet where it transects both the axial planar cleavage and bedding at oblique angles. Cleavage densities vary systematically across the area from typical values of 4–6 domains per cm in the Ugly Creek thrust sheet to values of 10–15 domains per cm along the Uwharrie thrust fault. Corresponding changes in the ratios of widths of microlithons to cleavage domains range from 4:1 in the Ugly Creek sheet to less than 2:1 in the Uwharrie and Mount Gilead sheets. Cleavage densities locally increase towards the leading fault of each thrust sheet. The significantly greater cleavage densities of the Uwharrie thrust sheet compared to lower values in the Ugly Creek thrust sheet record a progressive increase in strain towards the southeast across the thrust sheets. However, the lack of macroscopic strain indicators in the fine-grained rocks precludes assignment of values for the relative strains. Available data suggest that all cleavages and fault-related folds in the Albemarle area are related to progressive southeastward thrust movements along a subsurface detachment.

Stratigraphic interpretations of the area have been presented by Conley & Bain (1965), Stromquist & Sundelius (1969) and Milton (1984). Of particular interest to this study are those strata of the Albemarle Group which have been assigned to the Tillery Formation and parts of the McManus Formation of Conley & Bain (1965) or the Cid Formation of Stromquist & Sundelius (1969) and Milton (1984). These will be collectively referred to in this study as the 'Tillery'. Each thrust sheet discussed here is made up entirely of Tillery beds. In the eastern half of the study area klippen consisting of beds of the Uwharrie Formation rest upon the Tillery and associated thrusts (Fig. 3).

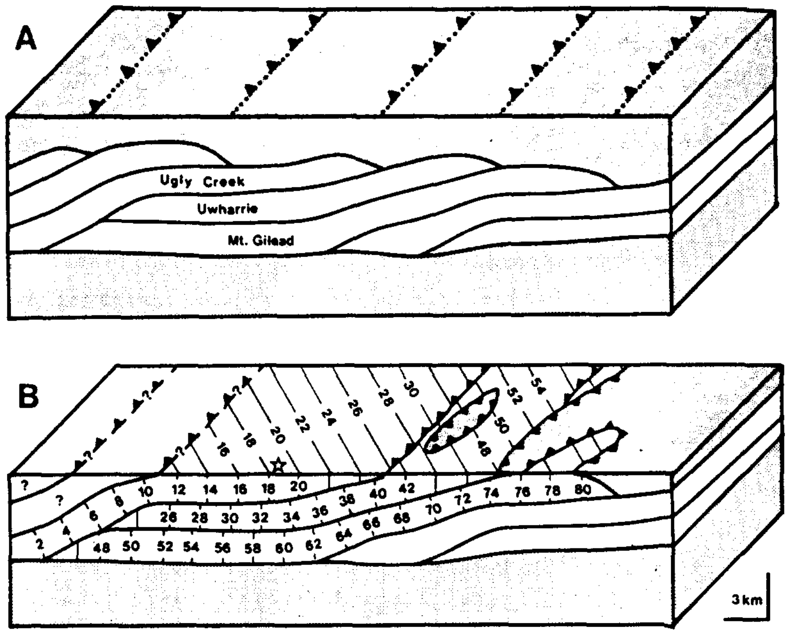


Fig. 3. Block diagrams that illustrate a possible schematic interpretation of the positions of the thrust sheets. The prominent block face is cut parallel to the displacement direction. In block diagram 'A' the upper stippled area denotes the Uwharrie volcanics and the lower stippled area corresponds to an unknown basement. Block B' has been stripped back to the present erosional surface. The star denotes the approximate location of Albemarle, North Carolina. The isopleth lines illustrate the lateral variation of an arbitrary sedimentologic parameter. The strike of the isopleths is normal to the paleocurrent direction.

The Tillery consists of medium-bedded to very thinly-laminated, non-foliated to foliated, chlorite–illite quartz argillite (*in sensu* Potter *et al.* 1980). Post-depositional diagenesis has recrystallized all but the quartz grains of most of the strata, leaving the original detrital quartz to 'float' in a matrix of chlorite and illite. Sorting, based on quartz grains, was good and in many beds the grains are vertically graded. Original quartz grain size varies from medium sand in the west to fine silt in the east (Fig. 4a). Maximum quartz grain size increases with increasing bed thickness (Fig. 5). Bedding is thickest to the west where it reaches up to 1 m, and diminishes eastward to laminations less than 1 mm (Figs. 4b & c). At individual outcrops in the westernmost and easternmost part of the study area bed thickness exhibits a log-normal distribution. In the central area bed thickness distributions are skewed greatly to the thinner beds beyond that which would be typical for a log-normal distribution (Fig. 6). Individual beds display a remarkable degree of uniformity of thickness over entire outcrops. Parting is strictly controlled by cleavage and varies from slabby to platy. Internal sedimentary structures, preserved as ghosts, can be seen on some slightly weathered outcrop faces and in polished sections. The ghosts result from slight color variations associated with differential amounts of lighter illite and darker chlorite. By association of the quartz grain size to the rock color it would appear that the chlorite was derived from the finer grained fraction of the original sediment while the illite was derived from the coarser fraction. Internal sedimentary structures observed in the strata include ripple cross-laminations, horizontal laminations, grading, rip-up clasts and rare trace fossils. Within individual beds the internal structures form complete, basal cut-out, truncated and truncated basal cut-out Bouma sequences (*in sensu* Bouma 1962, 1972). Truncated sequences are moderately common in the western part of the study area but were very rare to absent in the eastern part. Basal cut-out sequences are common in the west and pervasive in the east. We found a good correlation between individual bed thickness and sequence type (Table 1). Bedding amalgamation was infrequently observed in the western half. Also noted were infrequent chaotic beds suggestive of soft sediment slumps. We found no fossil remains within the Tillery, though a few are reported in the literature (Gibson & Teeter 1984).

Table 1. Measured thickness variations of the Bouma sequences observed in the Tillery throughout the entire study area. The $T_{a\text{–}e}$ sequence group also includes $T_{a\text{–}d}$ and $T_{a\text{–}c}$ sequences

Thickness (cm)	Sequence type				
	$T_{a\text{–}e}$	$T_{b\text{–}e}$	$T_{c\text{–}e}$	$T_{d\text{–}e}$	T_e
<0.1	—	—	—	—	51
0.1– 0.19	—	—	—	—	29
0.2– 0.39	—	—	—	12	27
0.4– 0.99	—	—	—	28	2
1.0– 1.9	—	—	3	13	—
2.0– 3.9	—	2	6	1	—
4.0– 9.9	2	9	4	—	—
10 –19	2	4	1	—	—
20 –39	1	1	—	—	—
40 –99	3	—	—	—	—
Median (cm)	18	7.0	2.8	0.5	0.1

Sole marks (flute marks) were very rare due to the development of cleavage. These gave a paleocurrent direction trending northeast. This was corroborated by analysis of a few ideally situated blocks with ripple cross-laminations and the general west to east variation in the character of the Tillery.

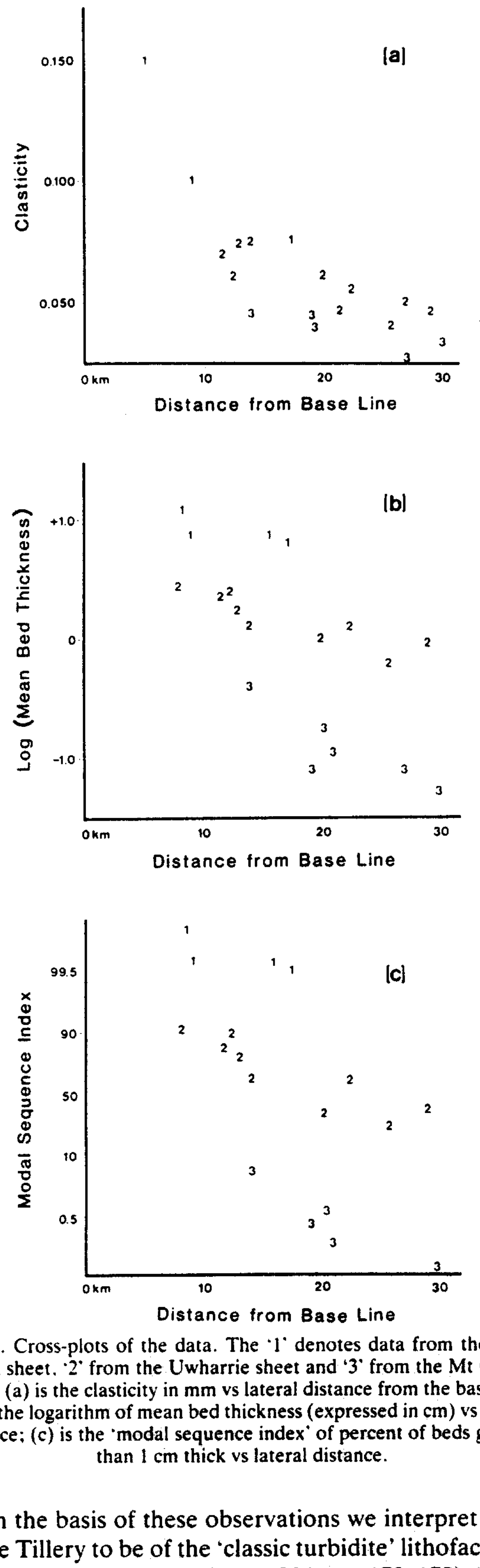


Fig. 4. Cross-plots of the data. The '1' denotes data from the Ugly Creek sheet, '2' from the Uwharrie sheet and '3' from the Mt Gilead sheet: (a) is the clasticity in mm vs lateral distance from the base line; (b) is the logarithm of mean bed thickness (expressed in cm) vs lateral distance; (c) is the 'modal sequence index' of percent of beds greater than 1 cm thick vs lateral distance.

On the basis of these observations we interpret most of the Tillery to be of the 'classic turbidite' lithofacies of Walker (1978, pp. 933–936 or 1984, pp. 172–173). Some of the Tillery exposed in the westernmost part of the study area may be transitional from the 'massive sandstone' lithofacies of Walker (1978, pp. 936–939 or 1984, p. 174). These strata unlike most of the Tillery have a few lenticular beds up to 1 m thick and 10 m in breadth which are suggestive of channels with an erosional base, graded basal conglomerates, and multiple sets of ascending ripples. We suggest that the Tillery in the westernmost part of the study area was deposited in the outermost region of the mid-fan of the submarine fan model of Walker (1978) or suprafan of Normark (1978). The remainder of the Tillery was deposited within lower fan and possibly basin plain of the Walker (1978) model.

METHODS

The sedimentological characteristics of the Tillery used in this study include grain size expressed as Carozzi's (1957) clasticity index, mean bed thickness, and a modification of Walker's (1967) proximality index (refer to the Appendix for a discussion and documentation of lateral variation of sedimentological character of turbidites). Clasticity was determined from thin sections of random grab samples from each locality. We generally used two thin sections from each of three to five grab samples. For each thin section we measured the maximum diameter of the five largest quartz grains. We then took the clasticity index to be the arithmetic average of those diameters.

Mean bed thickness was determined from cumulative percentage curves of the log of bed thickness plotted on probability paper. 'Bed' as used here refers to the entire depositional product of a sedimentation event, not just

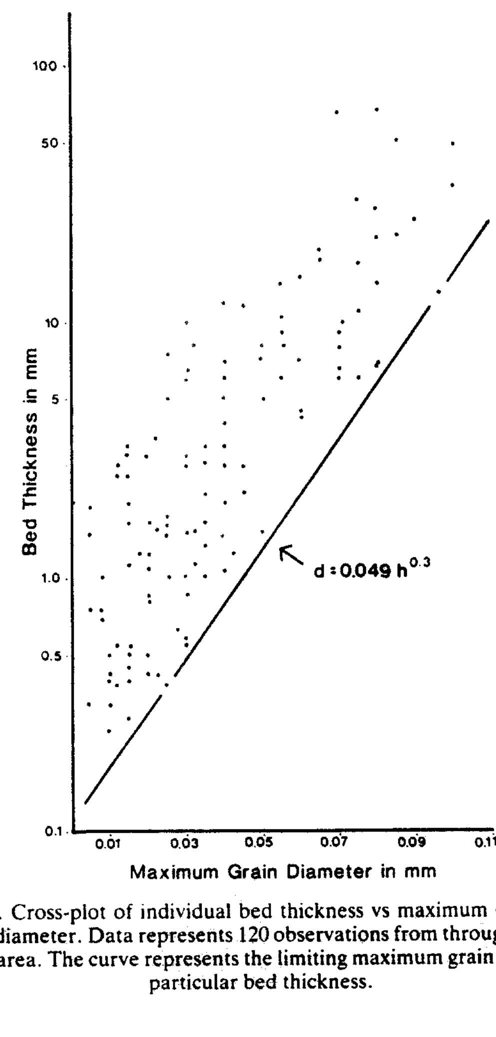


Fig. 5. Cross-plot of individual bed thickness vs maximum observed grain diameter. Data represents 120 observations from throughout the study area. The curve represents the limiting maximum grain size for a particular bed thickness.

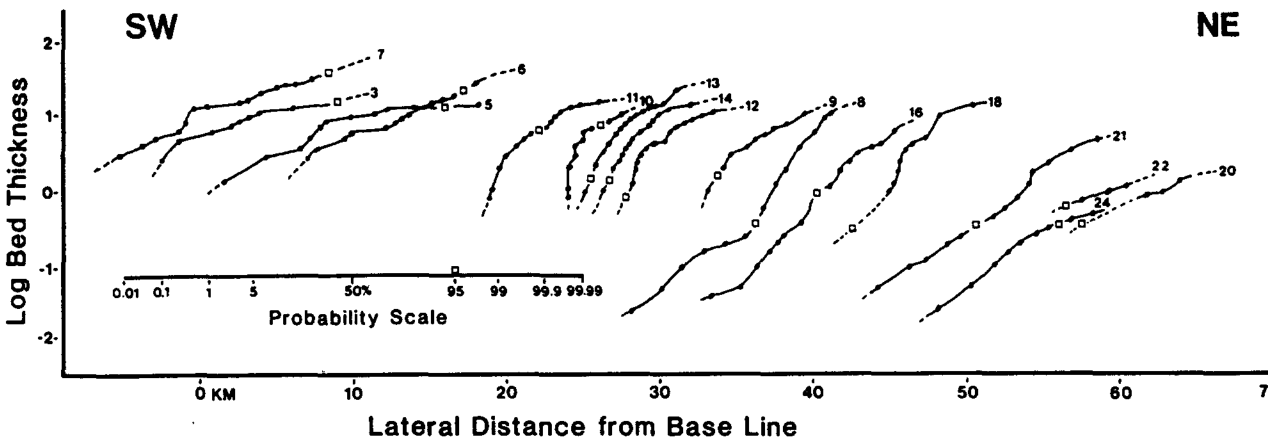


Fig. 6. Probability plots of bed thickness for each of the outcrops in the study area. The 95th percentile of each plot is normalized at its corresponding reconstructed lateral distance from the base line. The square denotes the logarithm of bed thickness (expressed in mm) at the 95th percentile. The numbers on each curve correspond to the outcrop numbers in Table 3.

the thick 'sandstone' portions of a turbidite sequence. Therefore, 'bed' encompasses even the finest of laminations as long as they represent a single episode of deposition. As mentioned previously, strata in the western and easternmost areas exhibited a log-normal distribution of bed thickness while those in the central area were strongly skewed toward the thinner beds. We attribute this to post-depositional compaction of the argillaceous portions of each layer. As a result the thicker beds (those greater than a few cm thick) exhibit minimal thinning due to a lack of a significant percentage of detrital argillaceous material while the thinner beds which originally contained a significant volume of detrital argillaceous material were significantly reduced in thickness. This preferential thinning or compaction is evident on the bed thickness probability plots where the thicker beds exhibit the same slope or variance (variance of the log of bed thickness was 0.3) or distribution function throughout the region whereas the thinner beds exhibit a significant deviation from that distribution function (Fig. 6). The original mean bed thickness was obtained by projecting a line representing the regional bed thickness distribution function through the data points representing the thicker beds. The mean bed thickness was then taken as the intercept of this line with the 50% line (Fig. 7).

At no outcrop could we make a positive identification of the type of sequence each bed or layer represented. However, as we could make a connection between bed thickness and sequence type (see Table 1), we defined an analogous parameter to the proximality index which we term the 'modal sequence index'. The modal sequence index 'P_m' is the percentage of beds over 1 cm thick. This is equivalent to the sum of the percentage of beds of the T_{a-e}, T_{b-e} and T_{c-e} types, and one half of the percentage of the T_{d-e} type:

$$P_m = A + B + C + D/2. \quad (1)$$

To minimize the bias introduced by previously noted post-depositional compaction of the argillaceous portions of the beds we took this percentage to be the intercept of the previously mentioned distribution function line and the 1 cm bed thickness line on the bed thickness probability plot (Fig. 7).

Calibration of the magnitude of fault displacement involved mapping the lateral variations of the selected sedimentological parameters within a 25 km wide transect which trended E–W (see Fig. 3 and Table 3). A reference or 'base line' was then struck on the maps in a direction that is normal to the down-paleocurrent direction and is positioned arbitrarily near the western end of the transect (Fig. 2). The base line is a straight line that

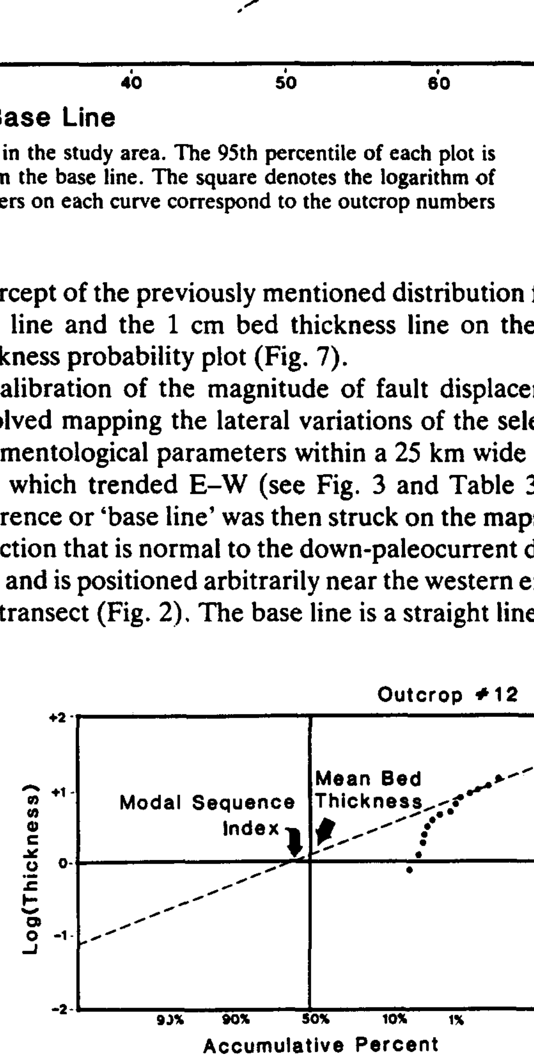


Fig. 7. Probability plot of the bed thickness data at outcrop No. 12 illustrating the method of determining mean bed thickness and modal sequence index. Dots represent actual data groupings. Dashed line represents the area wide log-normal trend of bed thickness projected through the data corresponding to beds greater than 5 cm thick. Accumulative percent scale is reversed from that of Fig. 6 in order to mark off the percent of beds greater than a particular thickness. Mean bed thickness taken as the intercept of the dashed line and the 50th percentile. Modal sequence index taken as the intercept of the dashed line and the 1 cm bed thickness line.

Table 2. Fault displacements as determined by: (a) clasticity; (b) mean bed thickness; and (c) modal sequence index

	Displacement (km)		
Fault	(a)	(b)	(c)
Ugly Creek Fault	11.7	19.3	18.3
Uwharrie Fault	19.6	29.4	29.5

Table 3. Data set. The numbers in column 1 correspond to the outcrop numbers on Fig. 2. The lateral distances in column 2 are relative to the base line; the negative value indicates a position to the west of the base line. Clasticity, column 3, is the average maximum diameter of largest quartz grains. Mean bed thickness, column 4, is determined from probability plots. Mean bed thickness, column 5, is determined from the arithmetic average of the bed thicknesses. Modal sequence index, column 6, is expressed as the percent of beds or stratification events greater than 1 cm thick. In column 7 the 'A' indicates the outcrop is within the Ugly Creek thrust sheet, 'B' the Uwharrie thrust sheet and 'C' the Mt Gilead thrust sheet

Outcrop No.	Lateral distance (km)	Clasticity (mm)	Mean bed thickness (cm)	Mean bed thickness (cm)	Modal sequence index (%)	Sheet
1	1.5	0.262	—	—	—	A
2	−4.3	0.217	—	—	—	A
3	9.0	0.100	7.59	9.26	99.7	A
4	5.0	0.150	—	—	—	A
5	15.7	—	7.41	9.21	99.7	A
6	17.3	0.076	6.30	9.79	99.5	A
7	8.5	—	11.75	17.80	99.97	A
8	22.2	0.056	1.26	0.23	62	B
9	20.0	0.063	1.12	0.42	56	B
10	12.3	0.059	2.51	1.12	90	B
11	8.0	—	2.82	1.26	91	B
12	13.8	0.075	1.32	0.33	65	B
13	11.5	0.051	2.24	0.52	85	B
14	12.7	0.074	1.78	0.45	79	B
15	21.3	0.047	—	—	—	B
16	25.5	0.041	0.63	0.22	26	B
17	26.8	0.050	—	—	—	B
18	28.7	0.046	1.12	0.17	38	B
19	27.0	0.026	—	0.08	—	C
20	20.8	—	0.11	0.09	00.1	C
21	14.0	0.046	0.40	0.13	6	C
22	20.3	—	0.18	0.18	0.8	C
23	19.0	0.044	—	—	—	C
24	19.3	0.041	0.08	0.09	00.02	C
25	30.0	0.033	—	—	—	C

defines a reference position from which all the outcrops have a relative lateral distance. The data for each parameter was then cross-plotted against the lateral distance from the base line (Figs. 4a–c). Data points were discriminated into groups based upon the thrust sheet to which they belong.

At this point it would have been useful to have known the actual equations for lateral variation of each parameter. The empirical relationships of Scheidegger & Potter (1971) are only slightly useful here in that they represent lateral variation of similar parameters in a different turbidite setting. To derive an approximation of the relationship for the Tillery within the area of the transect we started by working with the data from the Uwharrie sheet, the most extensive set of data. Working with just the mean bed thickness data from the Uwharrie sheet we derived an empirical relationship for lateral variation:

$$\log H = -0.03X, \qquad (2)$$

where X, an arbitrary starting point, has a value of zero when the mean bed thickness, H, is 1.0 mm. From the cross-plot of grain size vs bed thickness (Fig. 5) we derive the following empirical relationship between bed thickness, h, and grain size, d:

$$\log d = -1.31 + 0.3 \log h. \qquad (3)$$

To formulate an approximate lateral variation function for clasticity we equate the mean bed thickness H of equation (2) to bed thickness h of equation (3). We also equate clasticity, D, to the grain size, d of equation (3). Applying equation (2) to equation (3) we derive a lateral variation function for clasticity:

$$\log D = -1.31 - 0.009X. \qquad (4)$$

Equation (4) is only an analogous approximation of the actual clasticity lateral variation function in that h is an actual bed thickness with a corresponding maximum grain diameter, d, whereas H is a mean bed thickness for a group of beds which have an average maximum grain size, D.

Equation (2) was used to generate a specific curve form for the mean bed thickness as it varies laterally down current in the study area. Equation (4) was used in a similar fashion to generate a curve form for the clasticity index. Once the curve form for mean bed thickness was established it was used to derive a curve form for the modal sequence index. This was possible since the modal sequence index was derived from the bed thickness distribution curves which had a common variance throughout the area. By knowing the variance and the mean bed thickness for a specific distance X one can derive the percent of beds greater than 1 cm thick. The three curves were each plotted so that they had the same parameter scales and lateral distance scales as the cross-plots of the field data. At this point we found it advantageous to plot the field data for each thrust sheet separately on transparent paper.

The three field data cross-plots for the mean bed thickness were then overlaid on the curve form for the

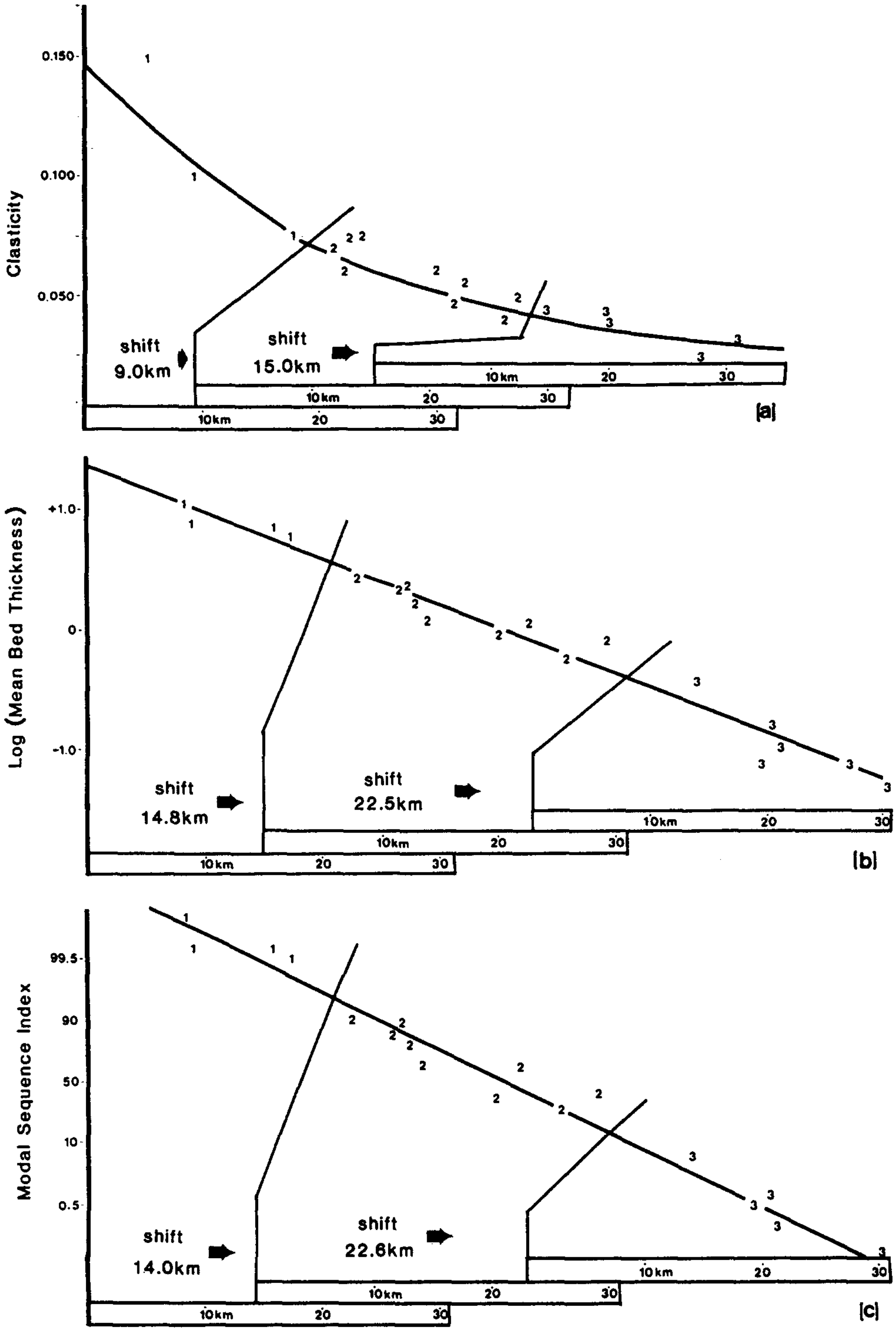
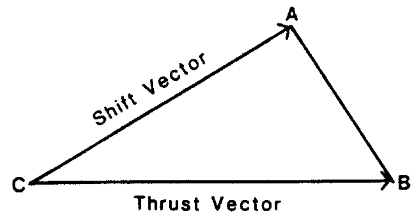


Fig. 8. Composite lateral variation curves for (a) clasticity, (b) mean bed thickness and (c) modal sequence index. Solid lines represent the curves that the data groupings were laterally shifted to by eye. Horizontal scales represent lateral distances from the base line. '1' denotes data drom the Ugly Creek sheet, '2' from the Uwharrie sheet and '3' from the Mt Gilead sheet. Clasticity scale in mm, mean bed thickness scale in logarithm of cm and the modal sequence index expressed as percent.

mean bed thickness. These three were then shifted upon the curve form until a best match 'by eye' was established (Fig. 8b). The post-shifting lateral distance between the base line on the Ugly Creek thrust sheet and the base line on the Uwharrie sheet was taken as the magnitude of the 'shift vector' of the Ugly Creek Thrust (Fig. 8b). Similarly the lateral distance between the base lines of the Uwharrie thrust sheet and the Mt Gilead sheet was taken as the magnitude of the 'shift vector' of the Uwharrie thrust. Similar shifts were done for the clasticity data and the modal sequence index (Figs. 8a & b). The shift vector is the apparent thrust displacement magnitude in the down-paleocurrent direction. The actual magnitude of thrust displacement is the magnitude of the shift vector divided by the cosine of the angle between the down-paleocurrent direction and the direc-



$$\text{Thrust Displacement} = \frac{CA}{\cos(ACB)}$$

Fig. 9. Geometric and trigonometric relationship between the shift vector and the thrust vector. The shift vector has a direction which is equal to the paleocurrent direction and a magnitude determined from the shifts of the data. The thrust vector has a direction which corresponds to the area-wide deformation direction and magnitude which equals the thrust displacement.

tion of thrusting (Fig. 9); this angle was taken as 40°. The results of these shifts and calculations are summarized in Table 2.

DISCUSSION

The close agreement of the displacements determined with the mean bed thickness and the modal sequence index and their difference from the values determined from clasticity does not necessarily mean that the clasticity is an inferior measure of displacement. The similarity of the results from the mean bed thickness and modal sequence index reflects the common origins of each, mainly bed thickness. The validity and accuracy of the method utilized here depends upon several constraints on the method and the selected parameters:

(a) post-depositional processes must not affect the regularity of the lateral variations;

(b) the direction of thrusting should be parallel or oblique to the paleocurrent direction, not be perpendicular to such;

(c) the parameter should be predictable and change at a sufficient rate to permit detection of the thrusts;

(d) the width of the transect should be small enough to exclude multiple source areas and to remove the effects of non-linear paleogeography so that one may assume an uniform down-paleocurrent direction throughout the area of the transect;

(e) the vertical sample size at each outcrop should be large enough to accommodate ephemeral or cyclic variations and the possibility of progradation of depositional facies.

Post-depositional diagenesis and strains have greatly modified the strata in that most of the original detrital grains are now lost with the exception of quartz. The tendency for an increase in the degree of elongation of quartz grains and frequency of observation of such from west to east across the area mimics the relative increase in strain as established by the cleavages. Locally, quartz grains become elongated within a few meters of the Uwharrie Thrust. In handling of the data we did not discriminate out sample sets that were affected by grain elongation.

The probability plots of bed thickness distribution suggest post-depositional preferential thinning of the argillaceous beds under the influence of increasing strains towards the east. The progressive addition of an argillaceous component in the original sediment towards the east enhances this effect. The problem of preferential thinning of the argillaceous beds was discussed in Methods. The method described there does not totally correct the situation in that it depends upon being able to position a regional variation function through the data representing the thicker beds. In the western part, where there are predominantly thicker beds, this was quite reliable; but progressively eastward this became less certain due to the reduced frequency of thicker beds.

Both the elongation of the quartz grains and the bed thinning affect the lateral variations of the related parameters and indicate that thrust displacements cannot be precisely determined. However, the effects of quartz grain elongation on estimates of thrust displacement are more pronounced in the east where elongation is greatest. Therefore, measures of thrust displacement determined from clasticity represent underestimates of displacement in these areas because elongated quartz grains appear to be larger and thus closer to the reference line than they actually are. On the other hand, thinning of beds results in a decrease in the mean bed thickness and a change in the modal sequence index. Measures of thrust displacements using these parameters are therefore overestimated because thinned beds appear to be further from the reference line than they actually are. The technique, as applied here, cannot precisely determine displacement, but when the results of the three parameters are combined one can bracket the true displacement. Thus displacement on the Ugly Creek Thrust is somewhere between a minimum of 11.7 km and a maximum of 19.3 km, and the Uwharrie Thrust has a displacement between 19.6 and 29.5 km.

Measurements of strain in these rocks are limited by the lack of suitable strain indicators. However, the effects of strain on the techniques described herein for determining thrust displacements can be estimated. Assuming a strain value of 0.5 for the clasticity in the Uwharrie thrust sheet (where strain effects are most evident) results in a correction of approximately 6 km to the underestimated displacement. Applying a similar value for thinning of the beds in the Uwharrie sheet yields a correction of approximately 8 km to the overestimated displacement. Both corrections are within the bracketed estimate of displacement provided by all three parameters. Higher strain values should lead to larger corrections, but these should still be within the established bracket of estimates of displacement. Thus, inclusion of strain data in the technique refines estimates of thrust displacements within the range established by the probability plots of clasticity, bed thickness and modal sequence index.

If the direction of thrusting is perpendicular to the paleocurrent direction then one cannot recognize any discontinuities in the lateral distribution of the sediment parameters even if the magnitude of thrusting is great. The accuracy of the method in this regard is zero for the perpendicular configuration and would seem to be maximal for the parallel situation, although a certain amount of obliqueness is desirable. The perpendicular configuration will conceal any structural shortening within the thrust sheet; the oblique configuration will exhibit data scatter but the overall trend of the data will be closer to the original depositional trend. The degree of obliqueness, 40°, observed here between the thrust direction and the paleocurrent direction explains some of the data scatter but it should not have affected the accuracy of the technique.

The classic turbidites of the lower fan and basin plain like those of the Tillery are well suited for the purpose described here in that they have a predictable change in character with lateral transport distance (see the Appendix). Sediments deposited in other parts of the submarine fan complex, the slope environment, or the shelf environment may not be as predictable. Predictability also includes being able to predict a curve form for the parameter. Curve forms for the parameters used here seem well founded (refer to the Appendix). However, it would have been better if the curve forms for the parameters had first been established in an undeformed terrain. Unfortunately in spite of the vast amount of literature available on the subject of lateral variation in turbidites there are only a few published reports giving the spatial relationships of the sedimentologic data and none sufficient in detail from which curves of lateral change can be generated.

The accuracy of the determination of thrust displacement magnitude depends upon the rate of change of the parameter with lateral distance relative to the magnitude of thrusting regardless of the shape of the curve form. A large thrust combined with rapid changes in a parameter would be easiest to resolve. Calibration of a small thrust may be impossible if the rate of change of the parameter is small. The lateral rate of change of the parameters used here seems appropriate to maintain accuracy. The reason for using the logarithm of mean bed thickness as a parameter instead of simple mean bed thickness was to maintain a reasonable rate of parameter change across the area. Changes in simple mean bed thickness vary rapidly in the upstream areas while remaining nearly constant in downstream areas. We similarly used the probability scale for the modal sequence index in preference to an arithmetic scale which would have been flat in the upstream area, steep in the middle and flat in the downstream area (an 'S'-shaped or sigmoidal curve form).

The shifting of the data is done by eye with the empirically derived curve being used only as a guide to the reconstruction of the actual predeformation curve form. The empirically generated curve forms are only partially analogous to the real lateral distribution curves. To have 'forced' the data to assume the empirical curve form would have given the results an unwarranted sense of truth and a non-random degree of error.

The width of the area of investigation or transect should be small enough to exclude multiple source areas and to remove the effects of non-linear paleogeography so that one may assume a uniform down-paleocurrent direction throughout the area of the transect. The ideal would be a simple linear transect taken down the paleocurrent direction. The problem with such an approach in the slate belt is a lack of available outcrops. It was therefore necessary to give the transect a finite width (25 km); and in doing so the possibility of a non-random error was introduced. If this error does exist it is probably small as the majority of fans described in the literature have widths much greater than 25 km (see Barnes & Normark 1985) and as the slate belt represents a volcanic arc with the Tillery in essence being described geometrically as an apron of coalesced ephemeral fans originating along the curvilinear trend of the arc. Furthermore, the parameters used here are not necessarily reflecting the lateral changes in sedimentology down a single fan but instead they are reflecting changes in the sedimentology of this apron at various lateral distances from the arc itself.

In the study area we utilized flute casts and the foreset bedding of ripples to determine the paleocurrent direction. Unfortunately flute casts are rare and limited to the western half of the study area and can only be recognized in weathered outcrops where cleavage is not well developed. Ripples of division 'c' of the Bouma sequence occur more extensively but require a two-faced or corner exposure of a slightly weathered quarry or road cut. As a result of these limitations we were forced to base our paleocurrent determination on a very few measurements (five or less per outcrop) at only four outcrops (Fig. 2). However, this may not have been too detrimental in that turbidite sequences exhibit a remarkable uniformity of paleocurrent directions at the outcrop scale (see Spotts & Weser 1964) and over a wide area (see Bouma 1962, fig. 19, Scott 1966, fig. 6, Schenk 1970, figs. 3–11, Nilsen 1985, fig. 2, Macdonald 1986, fig. 2).

There will invariably be some vertical variation in parameter value at each locality (for illustrations of vertical variations in bed thickness see Walker 1978, figs. 1 and 2, p. 934, Ricci Lucchi & Valmori 1980, fig. 6, p. 249, Walker 1984, fig. 2, p. 172, Eberli 1987, fig. 19, p. 381). The vertical sample size at each outcrop should therefore be large enough to accommodate ephemeral or cyclic variations and the possibility of progradation of depositional facies. The amount of strata that can be quantified at each outcrop is limited by the size of the outcrop and the time constraints of field work. In the study area very little significant vertical variation of parameters was evident at the few extensive outcrops (100 m). On the other hand, we did observe a significant variation on a meter by meter basis within a single section. All the sections used in the data base of this study represent 5 m or more of examined strata. We felt that being restricted to using sections of greater thickness would have introduced a greater error due to a paucity of data points than the error introduced from using the short sections. Furthermore, unless progradation exists, the error from vertical variation of parameters will be random and only result in data scatter about a mean. The possibility of significant error due to progradation does exist but it is not possible to evaluate such given the limited vertical exposure in the area.

The utility of some of the other possible parameters was explored during the course of this study. These included the frequency of lahars, slumps, and slides in a set thickness of strata, the number of laminations per centimeter, total number of stratification events per meter of section, and average (arithmetic mean) bed thickness. The frequency of lahars, slumps and slides proved unreliable due to the lack of extensive sections. These may prove useful with extensive drill core data or in areas of more extensive outcrops. It was possible to demonstrate a lateral change in the number of laminations per centimeter but that change was so gradual that the discontinuities across the faults was obscured by the data scatter. The number of stratification events 'beds' per meter of section works quite well and provides lateral shifts that are comparable to mean bed thickness and the modal sequence index. The average (arithmetic mean) bed thickness also works but suffers from the effect of differential thinning of the argillaceous beds. Values for this parameter are provided in Table 3.

SUMMARY

Displacement on the Ugly Creek Thrust just east of Albemarle, North Carolina, and within the Carolina Slate Belt is determined to have a minimum magnitude of 11.7 km and a maximum of 19.3 km. Displacement on the Uwharrie Thrust in the same area has a minimum magnitude of 19.6 km and a maximum of 29.5 km. Predictable lateral variations of grain size, bed thickness, and internal sedimentary structures of the 'classic turbidites' can be used to calibrate the magnitude of these thrust displacements. The accuracy of these displacements are subject to errors resulting from post-depositional processes, orientation of the thrust direction relative to the paleocurrent direction, the uniformity of the selected parameters, the constancy of the paleocurrents within the area of study, and the possibility of vertical variation in the measured parameters.

The procedure utilized here can be used elsewhere with the same sedimentological parameters or other parameters which have a similar degree of predictability. The three parameters employed here may not be universal in application, but they represent examples of what can be used. Application of this technique elsewhere will undubitably require tailor-made indices that reflect those parameters listed in Table A1; but the process of evaluation of the data and the constraints on the procedure will be the same.

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APPENDIX

LATERAL VARIANCES IN THE SEDIMENTOLOGY OF TURBIDITES

The term 'turbidite' is used here to denote the sediment and sedimentary rock depositional products of turbidity currents. A sequence of such strata is composed of literally thousands of 'layers' or beds each representing the passage of a single turbidity current. The concepts of turbidite sedimentology first appeared in the literature in the 1950s (e.g. Natland & Kuenen 1951, Carozzi 1957, Bouma 1959). Later studies have linked turbidites to submarine fans and proposed various models for the associated depositional processes and spatial relationships of the sediments (Bouma 1962, 1972, Normark 1970, 1978, 1980, Mutti & Ricci Lucchi 1972, Walker 1978, 1980, 1984, Nilsen 1980, Nilsen & Abbott 1981, Stow 1981, Macdonald 1986). One of the earliest observations noted about turbidites is the apparent lateral or down-current change in character of the sediments as expressed by various sedimentation parameters. Significant studies reporting these lateral changes in sediment character include Natland & Kuenen (1951), Carozzi (1957, Bouma (1959, 1962, 1972), Gorsline & Emery (1959), Dott (1963), Hand & Emery (1964), Kuenen (1964), Enos (1965, 1969), Scott (1966), Conolly & Ewing (1967), Middleton (1967), Walker (1967, 1978, 1984), Walker & Sutton (1967), Lovell (1969, 1970, 1971), Schenk (1970), Scheidegger & Potter (1971), McCabe & Waugh (1973), Nelson & Nilsen (1974), Stow (1976, 1979, 1981), Tasse *et al.* (1978), Ricci Lucchi & Valmori (1980), Stow & Shanmugam (1980), Piper & Normark (1983), Macdonald (1986) and Pilkey & Cleary (1986). The various parameters which have been observed to exhibit lateral changes are listed in Table A1.

Of particular interest are the lateral changes in grain size, bed thickness and internal sedimentary structures. Lateral variations in grain size within turbidite sequences have been reported by Carozzi (1957), Bouma (1962, 1972), Hand & Emery (1964), Walker (1967), Enos (1969), Schenk (1970), Scheidegger & Potter (1971), Nelson & Nilsen (1974) and Stow (1976, 1979, 1981). Grain size in recent turbidites has been expressed as the maximum or medium for a single

Table A1. Sedimentation parameters of turbidites which have been reported to exhibit lateral changes in character listed in decreasing order of frequency of citation. The down-current change is given as a general tendency only; in the earlier literature this would be the change going from proximal to distal

Parameter	Down current change
Sand to shale ratio	decrease
Bed thickness in general (maximum, mean or medium)	decrease
Grain size (maximum or mean)	decrease
Internal sedimentary structures (Bouma sequence)	see text
Frequency of sandstone bed amalgamation	decrease
Bedding regularity and sharpness	increase
Frequency of scours and tool marks	decrease
Degree of grading	increase
Unit thickness (isopac)	decrease
Percent shale	increase
Frequency of mud flake conglomerates	decrease
Frequency of chaotic beds	increase
Ratio of clay minerals (kaolinite to illite)	decrease
Frequency and type of trace fossils	variable
Frequency of channels	decrease
Mineralogical content (% quartz, % feldspar)	variable
Percent rock fragments	decrease
Heavy mineral content, especially biotite	increase
Feldspar ratios	variable
Frequency of concretions	decrease
Frequency of cone-in-cone structures	increase

bed. In dealing with ancient turbidites Carozzi (1957) proposed using a 'clasticity index' in which the maximum diameter of the largest quartz grains was measured from thin sections. Documented lateral changes from recent turbidites (Hand & Emery 1964, fig. 7, Nelson & Nilsen 1974, fig. 2) and single beds of ancient turbidites (Carozzi 1957, fig. 10) indicate that there is an exponential decrease in grain size with downcurrent distance. Grain size was evaluated semi-quantitatively by Scheidegger & Potter (1971) and expressed mathematically as:

$$d = C_5 X^{-0.5},$$

where d is the grain diameter, X is the lateral down-current distance and C_5 is a constant (Scheidegger & Potter 1971, equation 5, p. 45). Lateral variation in grain size in sequences of turbidites where many sedimentation events are represented will show a degree of complexity in the upper and middle fan areas due to the presence of channels (coarse-grained facies) and their adjacent levées and interchannel areas (fine-grained facies). However, in the lower fan areas where incised channels are absent the turbidite sequence will assume a simple lateral variation somewhat analogous to that of a single bed.

Lateral changes in bed thickness in ancient or modern turbidites have been reported by Natland & Kuenen (1951), Carozzi (1957), Bouma (1962, 1972), Enos (1965, 1969), Scott (1966), Walker (1967), Lovell (1969, 1970, 1971), Schenk (1970), Scheidegger & Potter (1971), Ricci Lucchi & Valmori (1980) and Macdonald (1986). Most authors when referring to 'bed' thickness are in general expressing the thickness of the sandstone beds or arenaceous part of a single sedimentation unit, though the total sand–shale couplet or 'layer' thickness has been utilized in some cases. Bed thickness has been expressed as the maximum bed thickness at a particular site or the mean thickness or the mode. Bed thickness at any one site has been demonstrated to exhibit an approximate log-normal distribution (Scott 1966, Scheidegger & Potter 1971, Ricci Lucchi & Valmori 1980) and therefore the mean thickness would be a more appropriate parameter than maximum or mode. Scheidegger & Potter (1971) based upon a semi-quantitative analysis of bed thickness, grain size and the interrelationship of each, have proposed the following mathematical expression of down-current bed thickness changes:

$$H_{tot} = C_{11} x^{-p-5/2},$$

where H_{tot} is the bed thickness, x is the lateral down-current distance, C_{11} is a constant and p is the 'grain-size distribution parameter' such that p is always larger than $-5/2$ (Scheidegger & Potter 1971, equation 12, p. 47). The mean bed thickness of a sequence of stratification events will show some complexity in the upper and middle fan areas and should be analogous to the above noted relationship in the 'classic turbidites' of the lower fan.

The orderly and predictable character of the internal structures of turbidite beds has been described by Bouma (1962, 1972) and Stow & Shanmugam (1980). The internal structures are commonly referred to as the 'Bouma Sequence' in which the ideal complete sequence of structures within a given stratification event is divided into five divisions which are from base to top: (a) graded or massive division; (b) lower division of parallel lamination; (c) division of current lamination; (d) upper division of parallel lamination, and (e) pelitic division (see Bouma 1962, pp. 49–52 or 1972, pp. 206–208). The sequence of Stow & Shanmugam (1980) has nine divisions which parallels the Bouma sequence but adds additional detail to the upper divisions. The discussion that follows utilizes the Bouma sequence (*in sensu* Bouma 1972). A complete Bouma sequence is symbolized, T_{a-e}. In outcrop each 'sedimentation event' will not necessarily represent a complete Bouma sequence; but instead some will have division 'a' missing, T_{b-e}, some will be missing both 'a' and 'b', T_{c-e}, some will lack 'a', 'b' and 'c', T_{d-e}, and some will have only division 'e', T_e. These are referred to as base cut-out sequences (Bouma 1962, p. 50). Other sequences will be missing one or more of the divisions above the lowest division, for example only division 'a' and 'b' might be present, T_{a-b}. These are referred to as truncated sequences (Bouma 1962, p. 50). Finally there are truncated, base cut-out sequences in which both some of the lower part and upper part of the ideal Bouma sequence are missing, T_b, T_{b-c}, T_{b-d}, T_c, T_{c-d} and T_d (Bouma 1962, p. 51).

Many studies have explored the nature of the lateral changes in the sequence of internal structures (Bouma 1962, 1972, Walker 1967, Walker & Sutton 1967, Lovell 1969, 1970, Stow 1980, Stow & Shanmugam 1980, Macdonald 1986). Within the 'classic turbidites' (*in sensu* Walker 1978, pp. 933–936, or 1984, pp. 172-173) these lateral changes include the progressive statistical downcurrent loss of the lower division due to waning turbidity current energy and changes in sediment load transport mechanism, and the loss in the upstream areas of the upper divisions due to erosion by successive turbidity currents. Walker (1967) described these lateral variations in terms of a 'proximality index' based upon the percentages of sedimentation events which began with division 'a' and 'b'. This was expressed as:

$$P = A + B/2 \quad \text{(equation 2 of Walker 1967)}$$

or

$$P_1 = (A - [A - E]) + B/2 \quad \text{(equation 3 of Walker 1967)},$$

where 'P' or 'P_1' is the proximality index, 'A' and 'B' are the percentages of beds beginning with division 'a' and 'b', respectively, and '[A − E]' is the percentage of beds beginning with division 'a' but thinner than 3 cm. Upstream areas were envisioned to have a high proximality index (upper limit of 100%) and that the value would diminish in a down paleocurrent direction (lower limit of 0%).

In summary, lateral variations of the sedimentation parameters of turbidites have been widely documented in the literature. Within the upper and middle fan regions these variations may be complex in form but in the lower fan areas the 'classic turbidites' exhibit simple lateral downcurrent variations in grain size, bed thickness and internal sedimentary structures. These simple lateral variations can be quantified for sequence of beds by application of the clasticity index (Carozzi 1957), mean bed thickness, and the proximality index (Walker 1967). In a down-paleocurrent direction the clasticity index, the mean bed thickness and the proximality index all decrease.