STATISTICAL ANALYSIS OF BED-THICKNESS PATTERNS IN A TURBIDITE SECTION FROM THE GREAT VALLEY SEQUENCE, CACHE CREEK, NORTHERN CALIFORNIA

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ABSTRACT: **This paper explores the use of a Monte Carlo adaptation of runs analysis to analyze turbidite sequences for the presence of asymmetric bed-thickness cycles. Waldron's test can be used to identify sequences that are dominated by either upward-thickening or upward-thinning cycles, but not both. Our adaptation of runs analysis provides a robust technique that can indicate the presence of local thickness trends that are different from those expected in random sequences, and can be used to evaluate the relative importance of upward-thickening and upward-thinning cycles. As a case study, 236 m of the Upper Cretaceous Sites Formation in the Great Valley Group were measured and described in detail along Cache Creek in northern California. This section had been previously interpreted as a succession of prograding submarine-fan-lobe deposits marked by asymmetric upward-thickening cycles. Application of Waldron's test indicates that the section is not dominated by upward-thickening cycles, as previously suggested. Monte Carlo runs analysis demonstrates that small-scale upward-thinning cycles are as common as upward-thickening cycles. The simple progradation of submarine fan lobes does not adequately explain the thickness patterns seen in the section. Application of Monte Carlo runs analysis to other turbidite sections would be useful for quantitative identification and comparison of turbidite bed-thickness cycles, which should lead to development of better turbidite facies models.**

INTRODUCTION

Interpretation of depositional environments in turbidite sequences relies heavily on analysis of vertical stratigraphic successions (Walker 1984). Upward-thinning (negative) sequences made up of turbidites with erosional bases are usually interpreted as the fill of submarine channels in inner and mid fan areas, whereas upward-thickening (positive) sequences of turbidites with parallel tops and bases were originally thought to result from progradation of submarine fan lobes (Walker 1984). Ricci Lucchi (1975) provided idealized examples of simple and complex patterns of turbidite bed thickness associated with positive and negative cycles.

Walker (1984) pointed out that recognition of these vertical patterns is subjective and questioned the reality of many such cycles described in the literature. In particular, he showed that some sequences can be reinterpreted from negative to positive, or vice versa, by making different choices for the beds that define the bases of the cycles (Walker 1984). Hiscott (1981) showed that some of the interpreted asymmetric cycles resulted from use of plots of bed thickness that contained an inherent bias, and demonstrated that a plot of turbidite bed number versus turbidite thickness would avoid that bias. Hiscott (1981) suggested that random stacking of turbidites can generate positive and negative cycles as convincing as those described from ancient deposits. In addition, Hiscott (1981) postulated that submarine fan lobes do not prograde, and, therefore, that interpretations of negative cycles as outer-fan facies are particularly suspect.

Lowey (1992) suggested a methodology to quantitatively identify upward-thinning and upward-thickening cycles in turbidite sequences. The method breaks a measured section into "megasequences" and tests each meqasequence for asymmetry using a number of statistical techniques. For that study, the definition of a megasequence was based on identification of packages of at least three beds thicker than 30 cm, and in which no more than six consecutive beds were thinner than 30 cm. Lowey (1992) pointed out that the number of beds he used to define a megasequence (three thick beds separated by no more than six consecutive thin beds), and the cutoff value used to separate thick beds from thin beds (30 cm), are not universal, but apply only to the turbidite section for which they were originally defined. For future studies, Lowey (1992) suggested that researchers determine the definition for a particular stratigraphic section on the basis of visual examination of the plot of bed thickness versus bed number, together with examination of statistics on the variation in bed thickness in the section. The number of resulting megasequences might need to be changed if it does not agree with the number of cycles expected in the section from Fourier analysis (Lowey 1992). While this methodology represents an improvement over methods previously used for determination of asymmetric turbidite cycles, it still appears to involve a great deal of subjective interpretation, and it would be difficult to compare results using this technique from different turbidite sequences.

Runs Analysis

Davis (1986) and Rock (1988) discussed a number of statistical methods for analyzing sequences of data. For studying the thickness patterns of turbidites, perhaps the most useful methods are runs about the median (RAM) and runs up and runs down (RUD). Heller and Dickinson (1985) and Waldron (1987) previously suggested the use of RUD for analysis of bed thickness patterns in turbidites. Here, we propose several modifications of the runs analysis technique that appear to be improvements on earlier implementations of the method.

Calculation of RAM can be used to examine a sequence for grouping of thick or thin beds, whereas RUD highlights the presence or absence of local trends. To determine the RAM, one compares the thickness of each bed to the median thickness of all the beds, and codes each bed as a zero if the thickness is less than the median, and as a one if the thickness exceeds the median. The number of runs of ones and zeroes are then counted, where a run is defined as an unbroken string of ones or zeroes.

Analysis of RUD appears to be particularly appropriate for identification of upward-thickening and upward-thinning bed cycles. In RUD analysis, a

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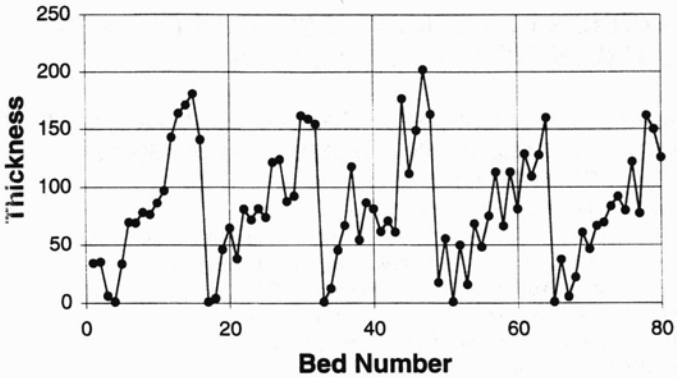


FIG. 1.—Idealized bed-thickness sequence characterized by upward-thickening trends with a strong component of random noise.

sequence is coded as a series of ones and zeroes by comparing the thickness of each bed to the thickness of the next bed (Rock 1988). If the following bed is thicker, then a one is recorded, otherwise a zero is recorded. Then the numbers of runs of ones and zeroes are counted; a run is defined as an unbroken string of ones or zeroes. If upward-thickening or upward-thinning sequences are present, the runs of ones and zeros are long and the number of runs tends to be small. If the stacking of beds is random, the runs tend to be short, and the number of runs is usually large. Rock (1988) described Edgington's test, which tests a sequence for randomness using the number of runs up and down. The test is two-sided, so the hypothesis of randomness is rejected if there are too few or too many runs.

Calculations of RUD are very sensitive to noise in the data. In a sequence that is highly structured but includes high-frequency noise (Fig. 1), calculation of RUD by the classical method described above may indicate that the number of runs of constant sign does not differ significantly from that expected in a random sequence. In an attempt to deal with this problem, Heller and Dickinson (1985) proposed a smoothing method based on a simple two-bed moving average. They used this smoothing method combined with Edgington's runs technique to test the hypothesis that a turbidite thickness sequence could have been the result of random processes, and applied the test to several turbidite sequences in California and Oregon. One problem with use of smoothing techniques is that Edgington's test cannot be used to test for randomness of the averaged sequence. Heller and Dickinson (1985) evidently did not realize this, and applied the test to averaged sequences in their paper. The error of this approach was pointed out by Waldron (1986).

Waldron (1987) proposed an improvement on Edgington's test that checks a sequence for the presence of asymmetric cycles. His test checks the signs of the differences between adjacent beds. In a sequence dominated by upward-thickening cycles, there should be many positive transitions and few negative transitions (Waldron 1987). If the null hypothesis of randomness is rejected, the sign of the Z statistic in Waldron's test indicates whether the sequence is dominated by upward-thickening or upward-thinning cycles. Waldron's method tests only for dominance of a section by one or the other type of asymmetric cycle; it will not detect a difference from randomness when both upward-thinning and upward-thickening cycles are present in the section.

To obtain more detailed information about the characteristics of a measured section, this study uses a Monte Carlo computer adaptation of runs analysis, adapted in part from the methodology discussed by Hiscott (1981), to compare the calculated RAM and RUD from a measured section with runs calculated from randomly generated sequences. RAM and RUD are calculated for each random sequence, with the RUD calculated using a robust method designed to smooth the effects of noise in the data. The Monte Carlo adaptation of robust runs analysis is discussed further in the Methodology section below.

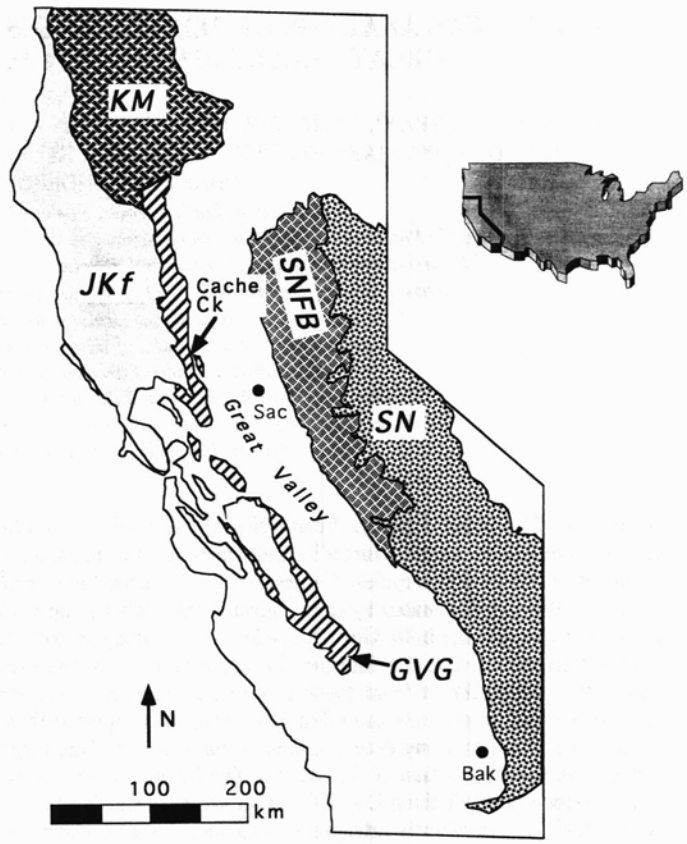
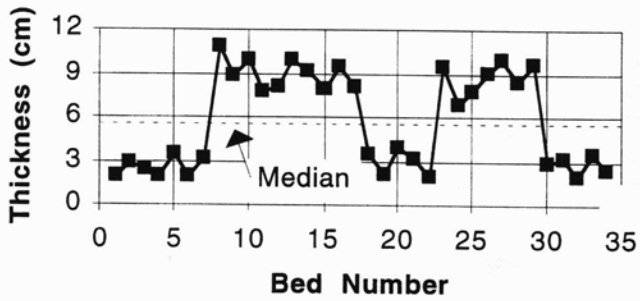


FIG. 2.—Map showing location of the Cache Creek section in northern California, western United States. Measured section of Sites Formation is within the Great Valley Group (GVG). Other tectonic regions highlighted include: JKf, Jurassic/Cretaceous Franciscan Complex; KM, Klamath Mountains; SNFB, Sierra Nevada Foothills belt; and SN, Sierra Nevada batholith. Locations highlighted include Sac (Sacramento) and Bak (Bakersfield). Adapted from Moxon (1990).

GEOLOGIC SETTING

Field data were gathered in the Cretaceous Sites Formation (Kirby 1943) of the Great Valley Group along Cache Creek in the western part of the Sacramento Valley, California (Fig. 2). The Great Valley Group is a succession of deep-water sedimentary rocks deposited in a fore-arc basin developed between the eastern continental-margin magmatic arc, represented by the present Sierra Nevada, and the associated trench to the west, represented by the Franciscan Complex (Ingersoll 1978). During the Cretaceous, about 9500 m of turbidites composed of mudstone, sandstone, and minor conglomerate were deposited in the Cache Creek area (Ojakangas 1968). The sediments were derived from volcanic, plutonic, and metamorphic rocks in the magmatic arc to the north and east (Dickinson 1971). Today, the Great Valley Group forms an uncomplicated east-dipping homocline along the western edge of the Sacramento Valley (Ojakangas 1968). The Sites Formation along Cache Creek is about 750 m thick and is dominated by massive graded sandstone turbidites. From the lack of channel morphology, the high sandstone/shale ratio, and the inferred presence of common upward-thickening cycles, Ingersoll (1978) postulated deposition of the lower and middle parts of the Sites Formation on a series of prograding outer-fan lobes.

A

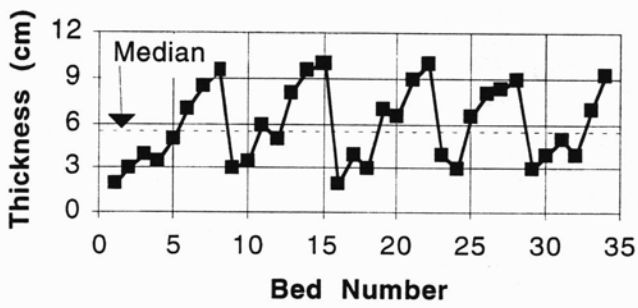


Runs about median of 5.5 cm:
0000000111111111100000111111100000

Robust runs up and down:
1001011000110010001011011100010 1

Summary Statistics:
Number of runs about median = 5
Number of runs up and down = 19
Number of long runs up (.ge. 4) = 0
Number of long runs down (.ge. 4) = 0
Longest run up = 3
Longest run down = 3

B



Runs about median of 5.5 cm:
0000011100101110001111001111000011

Runs up and down:
1111110011111001111100111100111 1

Summary Statistics:
Number of runs about median = 12
Number of runs up and down = 9
Number of long runs up (.ge. 4) = 5
Number of long runs down (.ge. 4) = 0
Longest run up = 6
Longest run down = 2

METHODOLOGY

Field data for the project were gathered by a group of 14 Stanford graduate students and faculty. The section chosen for measurement was split into five contiguous subsections, each about 50 m thick. Following collective observations and discussion for calibration, each subsection was measured by a team of two geologists recording data on a standardized graphic log. One person field-checked the work of all teams for consistency in characterization of bed thickness, sedimentary structures, grain size, and other attributes.

On returning from the field, each team coded the data from the graphic log for their subsection, and entered it into a spreadsheet program. Data recorded for each sedimentary unit included lithology, thickness, grain sizes of base and top, thickness of each Bouma division (Walker 1984) where present, as well as other descriptors (Murray 1992). A summary data file for the turbidites was prepared that included the total thickness of each turbidite, the thickness of each of the Bouma divisions, the maximum grain sizes, lateral continuity, and the presence of granules, water-escape structures, mud chips, and charcoal (Murray 1992). The turbidite thickness data were then statistically analyzed as described below.

Comparison with Randomly Shuffled Sequences

To obtain more detailed information about the characteristics of the measured section, a computer program was written that uses Monte Carlo simulation to compare the calculated RUD from the measured section with runs calculated from randomly generated sequences (Murray 1992). The program randomly shuffles the thicknesses from an original sequence, producing as many randomly ordered sequences as desired. This program is a computer adaptation of the procedure suggested by Hiscott (1981). RAM and RUD are then calculated for each random sequence, with the RUD calculated using a robust method designed to smooth the effects of noise in the data.

The robust method of analyzing the RUD compares the thickness of each bed to the thickness of the following three beds. If two out of three of the overlying beds are thicker, then a one is recorded, and the length of the runs is calculated as above. Figure 3A shows an idealized sequence with a strong grouping of thin beds and thick beds but no local trends (i.e., the transition from a zone of thick beds to one of thin beds is nearly instantaneous). Figure 3B shows a hypothetical section with grouping of thin beds and thick beds, but the zones of thin and thick beds are caused by local upward-thickening trends. Calculation of RAM would indicate significantly nonrandom sequences for the idealized sections shown in Figures 3A and 3B, whereas the number of RUD would be significantly different from a random sequence only for Figure 3B. By comparing the number of RAM and RUD for the original sequence and the shuffled sequences, it is possible to determine the probability that the observed sequence of thicknesses resulted from random processes.

In addition to testing the sequence for randomness, the program reports several statistics on the runs, both for the original sequence and for the random sequences generated by Monte Carlo simulation. The statistics include the number of RUD, the number of long RUD (i.e., the number of runs of constant sign longer than some threshold), and the lengths of the

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FIG. 3.—Diagrammatic examples of runs analysis, including runs about the median (RAM) and runs up and down (RUD) for two hypothetical stratigraphic sections. The runs up and down are calculated using the robust method described in the text. **A)** Example of runs calculations and summary statistics for a hypothetical sequence that does not show local trends between packages of thin and thick beds. **B)** Example of runs calculations and summary statistics for a hypothetical sequence that contains local upward-thickening trends. Note that the number of runs up and down is much smaller than in **A**. The number of long runs up and the length of the longest run up indicate the dominance of the sequence by upward-thickening cycles.

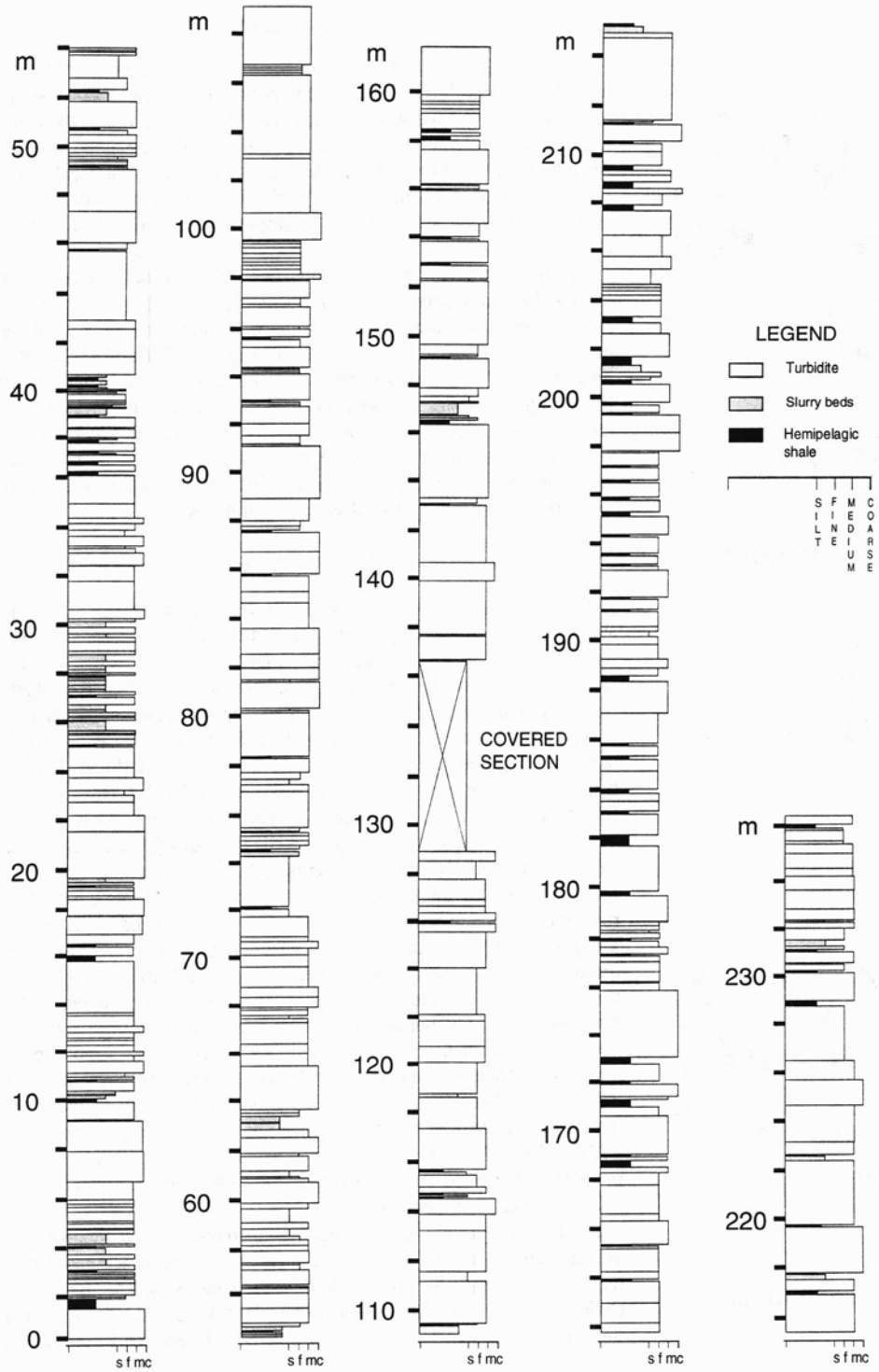

FIG. 4.—Measured section of the Sites Formation at Cache Creek, used as the basis for the statistical study.

longest run up and down. These statistics can be used to describe the properties of a sequence and to compare it to other sequences, including random sequences.

RESULTS

Figure 4 shows the measured stratigraphic section from the Sites Formation at Cache Creek. Of the 237 m of section, only one 7.7 m interval was covered. Three different types of sedimentation units were found in the section: turbidites, hemipelagic marine shale, and slurry beds. Most of the turbidites have sharp bases, parallel tops and bases, sole marks, and normal size grading. The Bouma sequence of turbidite divisions (Ta-Tb-Tc-Td-Tet-The) was used in describing each turbidite bed (Walker 1984), with Ta representing the massive graded division at the base of the sequence; Tb, the parallel sandy laminae of the upper-plane-bed regime; Tc, the rippled and convoluted division; Td, interlaminated silt and mud; Tet,

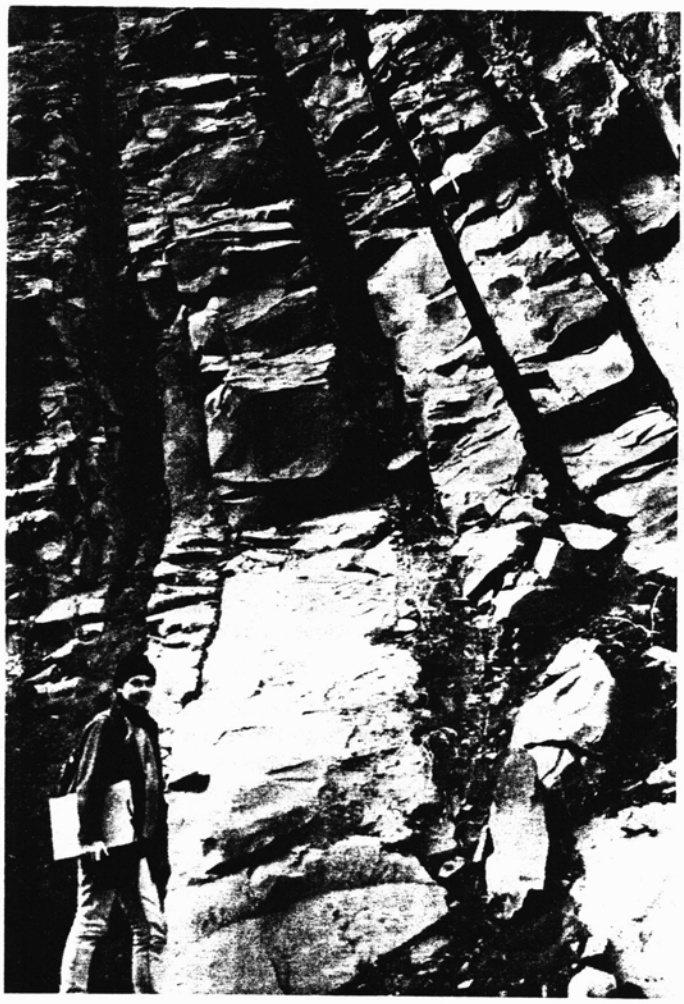

FIG. 5.—Characteristic turbidite section in the Sites Formation at Cache Creek, showing thick massive Bouma Ta divisions separated by thin Tb to Te divisions. Photograph by Christoph Heubeck.

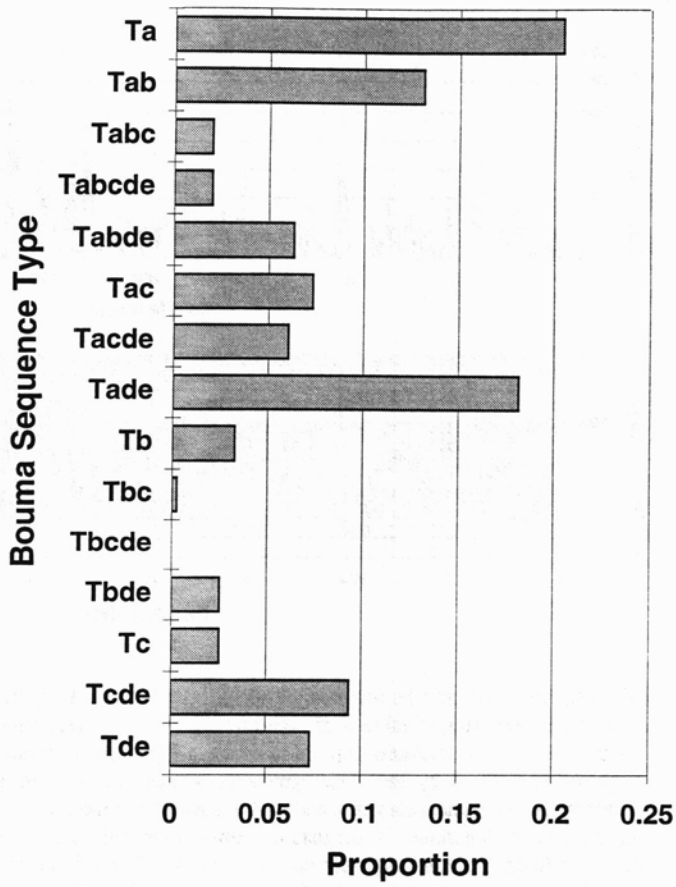

FIG. 6.—Proportion of turbidites falling within each Bouma sequence class. A complete Bouma sequence contains Ta, Tb, Tc, and Tde divisions. The incomplete sequences are missing one or more of the divisions.

the mud associated with the turbidite bed; and The, the hemipelagic mud deposited between turbidite events.

Hemipelagic marine shales (The) have not been identified separately from turbidite shale (Tet) in the Cache Creek section by previous investigators. Although they were not a principal focus of this study, hemipelagic marine shales were identified based on their darker color, greater fissility, and lower silt content (as estimated in the field) than associated turbidite shales (Tet divisions). The turbidite shale has a gradational contact with underlying turbidite sandstone divisions and a sharp contact with the overlying shale identified as hemipelagic, suggesting a different depositional mechanism for that shale (O'Brien et al. 1980). Color differences are one of the criteria identified by O'Brien et al. (1980) for distinguishing between turbidite shale and hemipelagic shale. The greater fissility in the hemipelagic shales may be due to parallel orientation of clay flakes, which O'Brien et al. (1980) suggested results from slow deposition of dispersed clay minerals. Hemipelagic shale beds in the measured section are thin, with a median thickness of 4 cm. Slurry beds were identified by their extremely poor sorting and the presence of floating sand grains and mudstone clasts in a muddy matrix. They represent deposits from watery, dilute debris flows that are transitional between turbidites and deposits of cohesive debris flows (Lowe 1982). Of the 616 sedimentary units described in the section, there are 399 classical turbidites (total thickness of 207 m), 171 hemipelagic shale beds (13.5 m), and 46 slurry beds (8.5 m). In terms of sediment thickness, turbidites constitute almost 90 percent of the section.

Most of the turbidites are laterally continuous at outcrop scale, with parallel tops and bases. There was little field evidence for erosional truncation or amalgamation of the turbidite beds. The maximum grain size of the majority of the turbidites is fine to coarse sand, although the turbidites have a maximum grain size ranging from silt to very coarse sand. Eleven percent of the turbidites contain granules and 14% contain mud chips.

Massive Ta divisions (Fig. 5) are the most common Bouma divisions in the section, and they are also the thickest, constituting most of the total thickness of the turbidites. Although complete Bouma sequences are present, they constitute only 2% of the turbidites. Mixed sequences in which one or more of the upper Bouma divisions are absent are most common in the section, including 35% of the turbidites (Fig. 6). Of the mixed sequences, the most common consists of thin turbidite Tde siltstone/shale divisions overlying much thicker, coarse Ta divisions. Judging by these results, the turbidites at Cache Creek were apparently deposited in a sand-rich environment dominated by rapid deposition of thick, massive Ta divisions.

Bed-Thickness Statistics

Figure 7 shows turbidite thickness plotted against bed number measured consecutively from the base of the measured section. This plot avoids biasing the observer towards identification of positive or negative cycles (Hiscott 1981). The mean thickness of the turbidite beds is 52 cm, with a geometric mean of 30.9 cm and a median thickness of 30 cm (Fig. 8). The data used for those statistics are based on the complete thickness of each

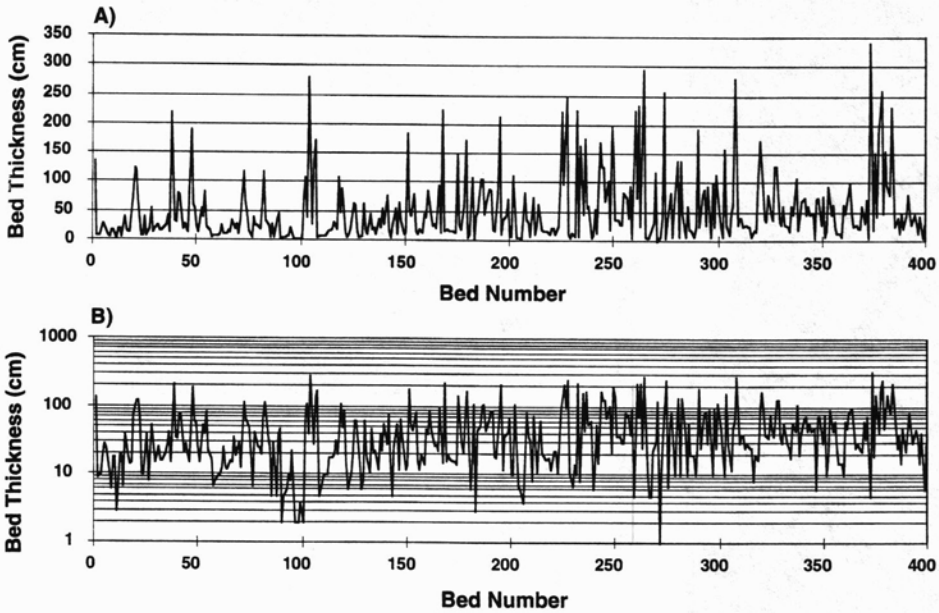

FIG. 7.—Plots of turbidite thickness vs. bed number (numbered from the base of the section). Plot using: **A)** linear thickness scale; **B)** logarithmic thickness scale.

turbidite, which will also be the basis of all further analyses. An analysis using just the sandstone thickness of each turbidite bed gave very similar results. The turbidite thickness appears to follow a lognormal distribution (Rock 1988), judging by the close agreement between the median and geometric mean thickness statistics, and on the linear plot of the cumulative frequency of the logarithms of the data on normal probability paper (Fig. 8B). In addition, a Kolmogorov-Smirnoff test (Rock 1988) did not detect a significant difference between the distribution of the logarithms of the turbidite thickness and a Normal distribution. There is a kink in the upper tail of the bed-thickness distribution (Fig. 8B) at a thickness of about 250 cm. The plot suggests that the thickest turbidites are somewhat thinner than would be expected by extrapolating the fit for the majority of the turbidites. The geological cause for the departure of the thickest beds from the thickness distribution observed for the majority of the beds is unknown, and no difference could be detected in the field between the Ta divisions of the dozen thickest beds and the rest of the turbidites. No signs of erosion were detected that might have resulted in a reduction of the thickness of the largest turbidite beds.

The turbidite thicknesses from Cache Creek were checked to see if they fit a power-law distribution, as suggested by Hiscott et al. (1993) and Rothman et al. (1994). For a power-law distribution to hold, the number of beds thicker than a thickness t must plot as a linear function of t, when plotted in a log-log graph. Figure 9 shows that the turbidite thickness data from Cache Creek do not fit a power-law distribution. Data from an extended Cache Creek section (Chester 1993) support this conclusion. Thus, the data from the Cache Creek section do not support the hypothesis of Rothman et al. (1994) that turbidite sequences without signs of significant erosion or amalgamation should fit a power-law distribution and show scaling behavior. Additional study of turbidite bed thickness distributions appears to be warranted to determine if there are consistent sedimentological differences between those turbidite sequences that fit a power-law distribution and those that do not that might be related to differences in depositional processes.

Asymmetric Bed-Thickness Trends

Waldron's (1987) test was applied to the turbidites in the Cache Creek measured section, after the sequence was smoothed by a two-bed moving average, in order to test for the dominance of upward-thickening asymmetric cycles, as proposed by Ingersoll (1978). The number of turbidites in the Cache Creek section is 399, with 185 negative transitions (m), 201 positive transitions (p), and 12 ties. The mean (μ_m) and standard deviation (σ_m) for the distribution of negative transitions for a sequence smoothed by a two-bed moving average are (Waldron 1987)

$$\mu_m = \frac{N - n}{2} = \frac{387 - 2}{2} = 192.5$$

$$\sigma_m = \sqrt{\frac{N + n}{12}} = \sqrt{\frac{387 + 2}{12}} = 5.69$$

where N is the number of turbidites minus the number of ties (399 − 12 = 387). For the test, m (the number of negative transitions) is modified to the value m' by making a continuity correction (Waldron 1987) that corrects for the use of a continuous distribution to test discrete data, yielding a value of 185.5. The Z statistic for the Cache Creek section is thus equal to

$$Z = \frac{m' - \mu_m}{\sigma_m} = \frac{185.5 - 192.5}{5.69} = -1.23$$

The absolute value of the Z statistic is less than 1.96, so the null hypothesis of randomness cannot be rejected at the 5% level.

Thus, Waldron's test indicates that the Cache Creek section is not characterized by upward-thickening asymmetric cycles, as proposed by Ingersoll (1978). The test also indicates that the sequence is not dominated by upward-thinning cycles. It is important to note that Waldron's method tests only for dominance of a section by one or the other type of asymmetric cycle—it does not detect a difference from randomness when upward-thinning and upward-thickening cycles are both present.

Runs analyses were then used to test for the presence of bed-thickness trends, including grouping of thick-bedded and thin-bedded units and asymmetric bed-thickness cycles. For both RAM and RUD, calculations were made on the measured sequence of beds, then compared with the results from 500 sequences generated by randomly shuffling the turbidites using the program written for this study (Table 1). The number of RAM for the Cache Creek sequence was 146. The mean number of RAM for the 500 randomly shuffled sequences generated by the Monte Carlo method was 193, with a standard deviation of 10.4 (Fig. 10A). Assuming that the num-

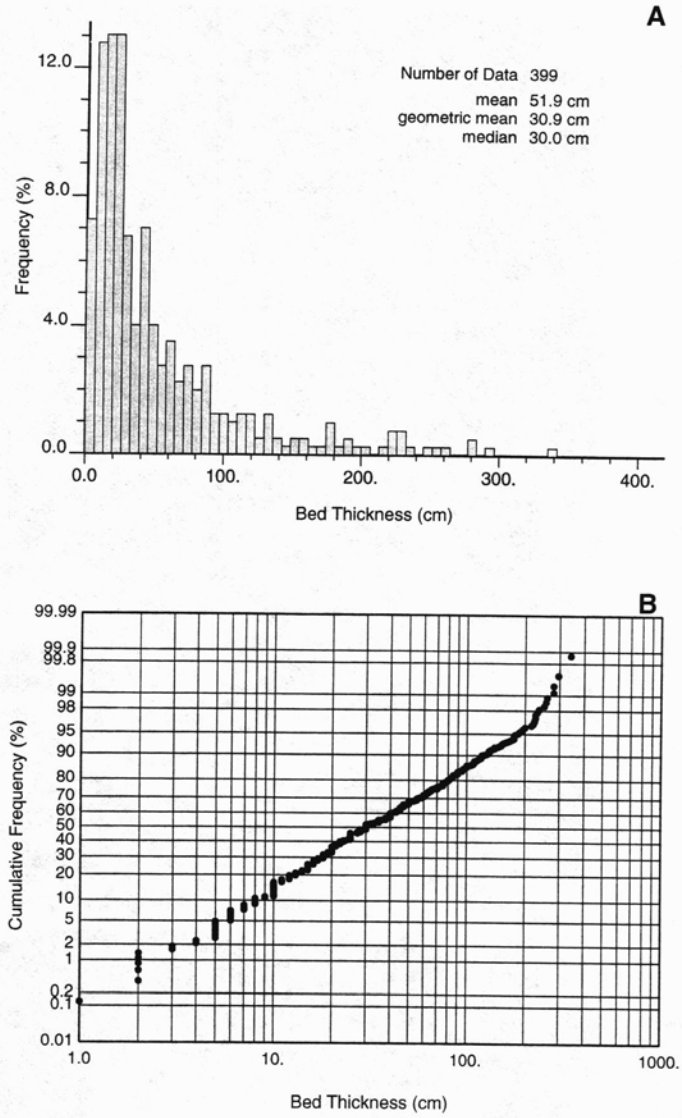

FIG. 8.—**A)** Histogram of the thickness of the turbidite beds; **B)** log-probability plot of turbidite thickness. The data in the log-probability plot are not binned. The apparent stacking of observations at certain measurement lengths in the log-probability plot (e.g., 2, 5, and 10 cm) is caused by rounding during collection of the thickness data in the field by geologists measuring the section.

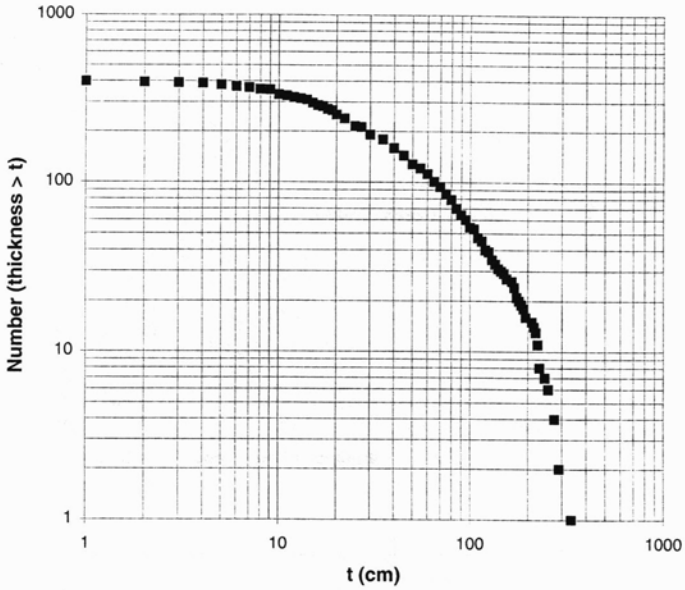

FIG. 9.—Log-log plot of the number of Cache Creek turbidite beds thicker than a thickness t as a function of t. The plotted data are not described by a linear function, indicating that the Cache Creek thickness data do not fit a power-law distribution.

ber of RAM for the randomly shuffled sequences fit a Gaussian distribution (which appears reasonable from Figure 10A), the probability that the number of RAM observed in the Cache Creek sequence could have arisen from random processes is essentially 0 ($Z = -4.5$). This extremely low probability is supported by the minimum number of RAM observed in the 500 randomly shuffled sequences (164), which easily exceeds the 146 RAM measured for the Cache Creek sequence. The RAM results indicate a strong tendency for beds to be grouped into packages of thick-bedded and thin-bedded turbidites.

There were 183 RUD in the measured section at Cache Creek, whereas the 500 randomly shuffled sequences had a mean of 209 RUD, with a standard deviation of 10.5 (Fig. 10B). Assuming that the RUD for the randomly shuffled sequences follow a Gaussian distribution, the probability that the RUD observed in the Cache Creek turbidite sequence could have arisen by random processes is approximately 0.01. Only four of the 500 randomly shuffled sequences had RUD less than or equal to 183. Statistics from the RUD analysis indicate that the Cache Creek section had a longer maximum run up, fewer runs of length 1, and more long runs (≥ 5) down than the random sequences (Table 2).

There are local thickness trends that appear to be well developed, for example the upward-thickening trend between turbidites 108 and 118 and the upward-thinning trend from beds 198 to 206 (Fig. 7). Both upward-thickening and upward-thinning bed sequences are present in the section. Figures 11 A and B show two upward-thickening cycles, one of which (in Figure 11A) appears to belong to a larger-scale upward-thinning cycle. A smaller upward-thinning cycle is shown in Figure 11C. There are 8 long upward-thinning sequences (a run of five, calculated using the robust method) and 4 long upward-thickening sequences. This suggests that upward-thinning cycles are more common in the Cache Creek section than previously noted.

Waldron's test indicates that the Cache Creek section is not dominated by either upward-thickening or upward-thinning asymmetric cycles. Comparison of runs analyses of the Cache Creek section and shuffled sequences suggests that the thickness of the turbidite beds did not result from random processes, and that asymmetric cycles are more common than one would expect from a random shuffling of the beds. However, both upward-thickening and upward-thinning cycles appear to be present, in subequal num-

TABLE 1.—*Results of runs analysis*

Runs about median	
Total Runs for Cache Creek section	145
Minimum from Monte Carlo simulations	164
Average from Monte Carlo simulations	193
Runs up and down	
Total runs for Cache Creek section	183
Average of 500 Monte Carlo simulations	209
Minimum of 500 Monte Carlo simulations	177
Number of simulations with RUD ≤ RUD of Cache Creek section	4
Number of long runs up (≥ 5) for Cache Creek section	4
Number of long runs down (≥ 5) for Cache Creek section	8
Longest run up at Cache Creek	10
Longest run down at Cache Creek	7

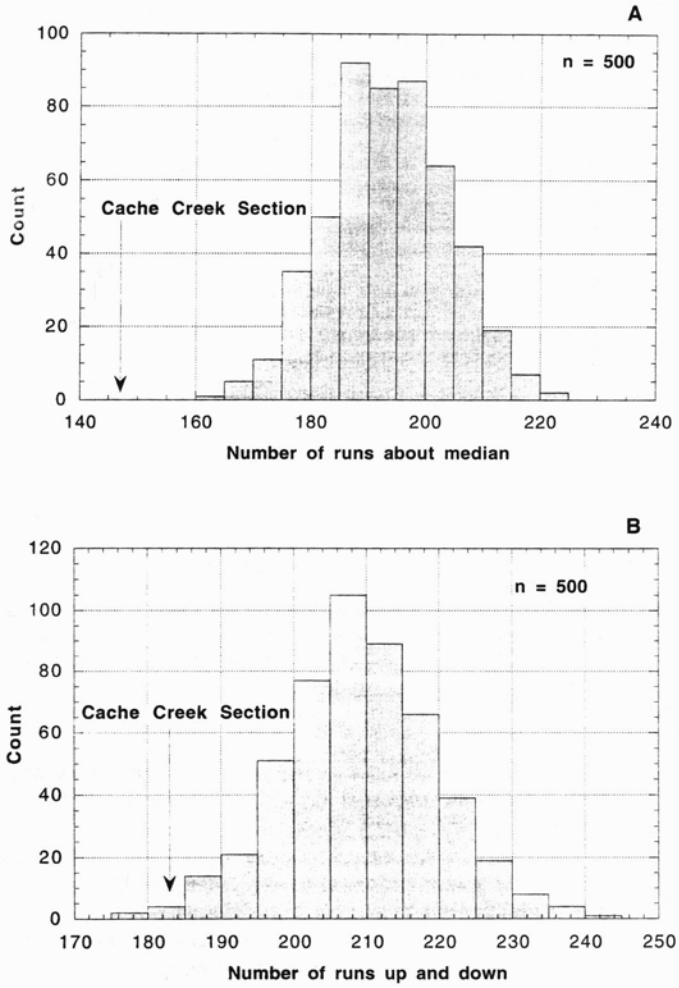

FIG. 10.—Monte Carlo simulation results. Histograms of **A**) runs about the median and **B**) runs up and down, for 500 simulated turbidite sequences generated using the thicknesses from the Cache Creek section. The Cache Creek section had 145 runs about the median, which is smaller than the number of runs about the median for any of the 500 random sequences. There were 182 runs up and down, which is less than the number of runs for 99.2% of the random sequences.

bers, which agrees with the results indicated by the application of Waldron's test.

CONCLUSIONS

This paper presents an objective and quantitative methodology for evaluation of bed-thickness sequences in stratigraphic sections. The section measured in the Sites Formation along Cache Creek shows complex vertical patterns in turbidite thickness. One of the strongest patterns observed is the bundling of turbidites into alternating packages of thick and thin beds. This suggests the presence of significant short-term variations in the magnitude of the turbidity flows, in the path of those flows, or in the amount of sediment supplied to the basin.

TABLE 2.—*Statistical comparison of runs up and down for Cache Creek and 500 random sequences*

	Number of Runs	Max Run Length	Runs Up of Length 1	Runs Down ≤ 5
Cache Creek	183	10	36	8
Mean of random	208.606	5.844	49.538	3.458
Std. deviation	10.471	1.011	7.231	1.781
Z value	−2.446	4.112	−1.877	2.551
P value	0.007	0.000	0.030	0.005

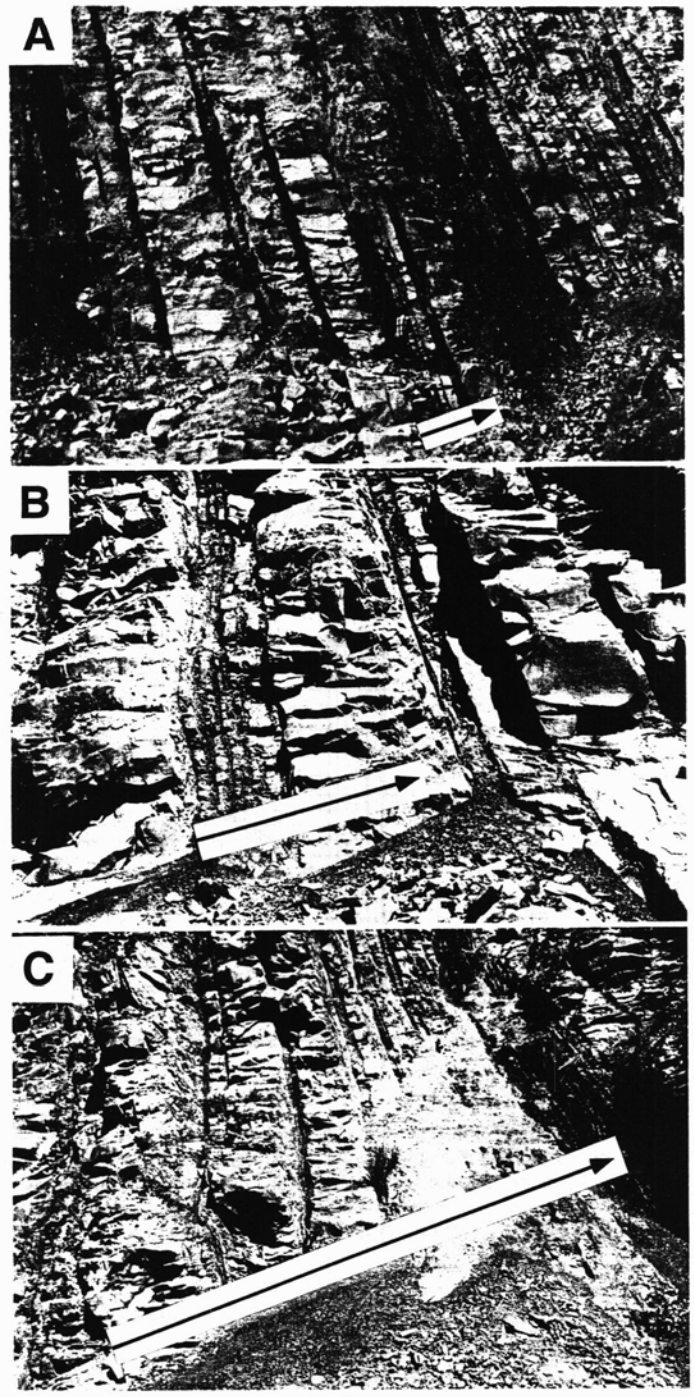

FIG. 11.—Upward-thickening sequences (**A** and **B**), and an upward-thinning sequence (**C**). Note that the small upward-thickening sequence in **A**, which is the sequence from Bed 108 to Bed 118 that is noticeable in Figure 7B, appears to be part of a larger-scale upward-thinning sequence (Bed 100 to Bed 150). Upsection is to the right in all three photographs.

Our results indicate that the Sites Formation at this locality is not characterized by a succession of upward-thickening cycles as proposed by Ingersoll (1978). In our study upward-thickening sequences are defined using

choice of a "base" or starting point for the upward-thickening cycles. The robust method of measuring RUD shows that the section also contains upward-thinning sequences, which appear to be at least as common as upward-thickening sequences. Application of Waldron's test to the Cache Creek section confirmed that the section is not dominated by upward-thickening asymmetric cycles.

The methodology proposed here appears to hold promise for providing an objective and quantitative description of turbidite bed thickness sequences. By comparing the statistical results from a measured section with the statistics calculated on randomly shuffled sequences of the same thickness distribution, it is possible to identify attributes of the sequence that differ significantly from a random sequence. Identifying other turbidite sequences with the same nonrandom attributes, followed by detailed geologic examination of those attributes, could lead to an improved understanding of the depositional environment of the turbidite sequences. This should lead to a more accurate classification of turbidite sequences, and better facies models for turbidites. The method could also be extended to sequences from other depositional environments that appear to have bed-thickness trends, such as fluvial and deltaic sequences.

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