Mathematical Geology, Vol. 34, No. 5, July 2002 (© 2002)

Statistical Evaluation of Compositional Differences Between Upper Eocene Impact Ejecta Layers[1]

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Melt droplets formed by the impact of a large meteorite impact event(s) have been found in upper Eocene marine sediments from the Atlantic, Pacific, and Indian oceans. The number of discreet impacts that occurred to form these melt droplets can be gleaned by compositionally analysing the droplets and establishing the number of distinct groups. Previous studies have inferred two, three, or more source impact events, although we believe the statistical techniques used to distinguish the groupings are open to criticism. Multivariate and univariate analysis (including discriminant analysis) of the major-element composition of an increased data set of impact melt ejecta droplets have been performed. The results demonstrate that the uppermost ejecta layer is geochemically distinct from other late Eocene melt ejecta. Our statistical analysis suggests two underlying, purportedly stratigraphically separate ejecta layers, possess minimal differences that cannot be distinguished clearly from one another by discriminant analysis, which adds to the plausibility that they have a common source. Finally, our results reveal apparent disparities between the new major-element data from this study and data compiled from existing sources.

KEY WORDS: microtektite, microkrystite, multivariate analysis, compositional means, discriminant analysis.

INTRODUCTION

Pulverized and melted rock ejected from its source region by the impact of a large meteorite or cometary body is known as impact ejecta. The geochemical composition of this ejecta typically reflects that of the target rocks at the impact site, as the impacting body is vaporized and contributes little to the ejected melt. This ejecta is locally preserved in the sedimentary rock record. However, correlating this material back to its source impact structure is rarely straightforward, particularly if impact ejecta occurs in several closely-spaced layers in the sedimentary record and/or several impact structures are known to have occurred at the time of the ejecta

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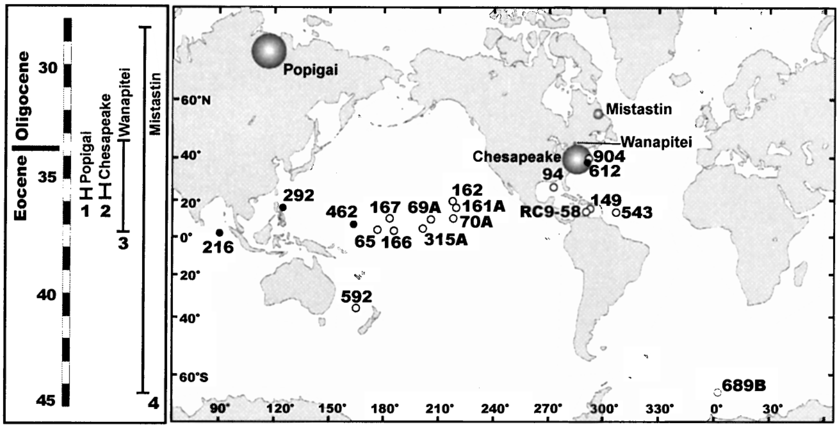

Figure 1. The four upper Eocene impact structures and Ocean Drilling Program and Deep Sea Drilling Program sites containing upper Eocene impact ejecta. Filled circles define sites from which microkrystites and microtektites have been extracted for major-element analysis. The size of the shaded circles on land are proportional to the impact structure diameter: Popigai, Siberia (100 km diameter); Chesapeake Bay, USA (85 km); Mistastin, Canada (28 km); and Wanapitei, Canada (7.5 km) (data from Grieve and others, 1995). The age of the impacts have been established based isotopic dating of impact melt rocks. (1) Bottomley and others (1997); (2) Site 612 tektites (Obradovich, Snee, and Izett, 1989); (3) Winzler, Lum, and Schumann (1976); (4) Mak and others (1976). All are ^{40}Ar/^{39}Ar plateau ages except (3), which is a K–Ar age. Ages (3) and (4) were recalculated using the decay constants of Steiger and Jäger (1977).

deposition. Such is the case for the late Eocene, during which four impact events of various sizes occurred (Fig. 1). The actual number of ejecta layers in the upper Eocene marine sediments generated by these impacts have been controversial. Workers have inferred two (Glass and others, 1985; Glass and Burns, 1987), three (D'Hondt, Keller, and Stallard, 1987; Keller and others, 1987), or more (Hazel, 1989) ejecta layers on the basis of biostratigraphic correlations between sample drill cores or compositional differences between the ejecta layers (Fig. 2). Here we focus on the chemical compositional variation of the impact ejecta layers in order to elucidate the number of compositionally discrete layer populations, and thus the number of impact events represented in the sedimentary record.

Several previous statistical analyses of impact melt ejecta compositional data obtained by microprobe analysis (e.g., D'Hondt, Keller, and Stallard, 1987) focus mainly on R-mode and Q-mode factor analysis. These techniques calculate linear combinations of the major-element oxides, called "factors." The hope of the analysts (e.g., D'Hondt, Keller, and Stallard, 1987) is that these factors, as well as the comparison of factors between purportedly different layers will indirectly allow the layers to be distinguished from one another. However, the technique is better suited for descriptive purposes than for inferential purposes (e.g., Walden, Smith,

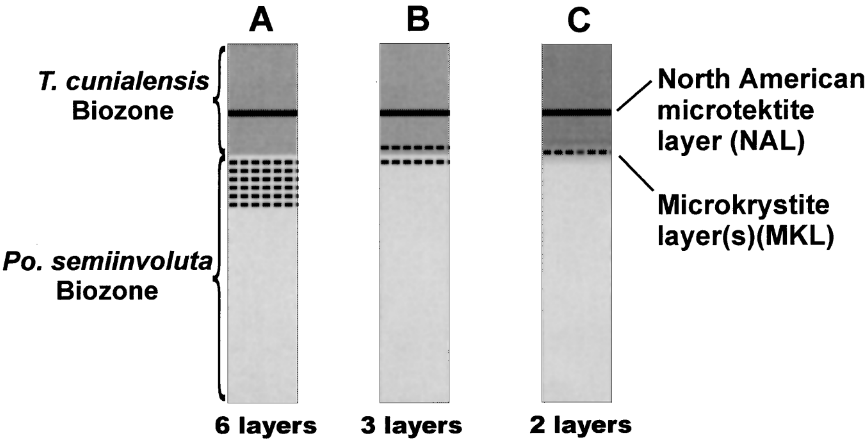

Figure 2. The principal interpretations of the number and stratigraphic location of upper Eocene impact ejecta layers in marine sediment cores shown in a composite section. Individual cores typically contain a microtektite layer alone, or a microtektite layer above a single microkrystite layer. Schematic sections are based on the reports of (A) Hazel (1989); (B) D'Hondt, Keller, and Stallard (1987); and (C) Glass and Burns (1987). Proponents of three discrete layers (B) distinguish the two proposed microkrystite layers based on subtle major-element differences and because they occur in the uppermost part of the *Turborotalia cunialensis* biozone in some cores, and in the *Porticulasphaera semiinvoluta* zone in others.

and Dackombe, 1992). Hence, the main objective of this paper is to illustrate and apply the use of other existing complementary statistical techniques, which are better suited for a formal comparison of the ejecta layers. In particular,

1. we consider tests (MANOVAs, ANOVAs, and 2-sample *t* tests), as well as visual displays like boxplots, for assessing whether the underlying mean vector compositions differ or not, and for determining which components, if any, best represent the differences in mean vector compositions; and
2. we report on confidence intervals for mean compositions, and we use discriminant analysis and its associated predictive ability to elucidate the practical significance of differences in the ejecta layers.

IMPACT EJECTA

Late Eocene impact ejecta has been identified in oceanic muds from the Indian, Pacific, and Atlantic Oceans, the Caribbean Sea/Gulf of Mexico and the Weddell Sea, off the coast of Antarctica (Glass and Koeberl, 1998; Glass and Zwart, 1979; Keller and others, 1987; Swinski and Glass, 1979) (Fig. 1). Ejecta also occurs on land in the states of Texas and Georgia, Martha's Vineyard in Massachusetts, and on the island of Barbados (Barnes, 1963; Kaye, Schnetzler,

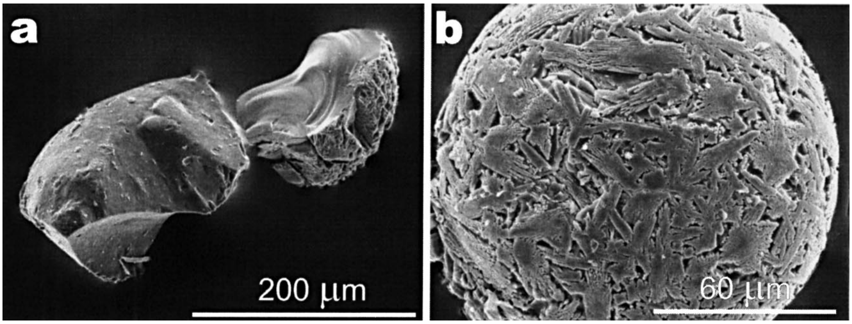

Figure 3. Secondary electron images of (a) fragmented North American layer (NAL) microtektites exhibiting conchoidal fractions, and (b) microkrystites (MKL) displaying crystals of diopside.

and Chase, 1961; Sanfilippo and others, 1985; Saunders and others, 1984). There are two distinct types of Eocene ejecta. The first type comprises glassy spheres, fragments, teardrop, and dumbbells that are generally pale green to brown and vesicular (Fig. 3(a)). These glassy ejecta are known as tektites when greater than 1 mm in diameter, and microtektites when smaller. They increase in size towards the eastern seaboard of the United States suggesting that they originate from the Chesapeake Bay impact structure in Virginia (Poag and others, 1994). This is corroborated by their isotopic composition that is consistent with melting of impact target rocks from this region (Glass and others, 1995; Stecher and others, 1989). These microtektites and tektites collectively define the North American strewn field. The second group of late Eocene ejecta comprises principally crystalline, not glassy, spheres and fragments that are known as microkrystites (Fig. 3(b)). These are generally opaque and range in colour from cream to black. They occur stratigraphically below the North American layer in drill cores, indicating that they were derived from a slightly older impact event. Their provenance from an impact structure distinct from that which generated the North American layer tektites is supported by their contrasting composition range (Fig. 4). Recent isotopic analyses of these microkrystites indicate that some of the analyzed fractions have an isotopic signature similar to that of impact melted rocks in the Popigai impact structure, Siberia, from which they were likely derived (Whitehead and others, 2000). Other microkrystite fractions do not possess a clear affinity with Popigai. This, coupled with the existing controversy regarding the actual number of discrete microkrystite layers, requires a reevaluation of the statistical methods that have been used by previous studies to subdivide the microkrystite into several layer populations.

COMPOSITIONAL ALTERATION

Examples of extreme leaching in groundwater-hydrated volcanic glass, including K, Si, Fe, Na, Ti, and Mn (e.g., Mungall and Martin, 1994) indicate that

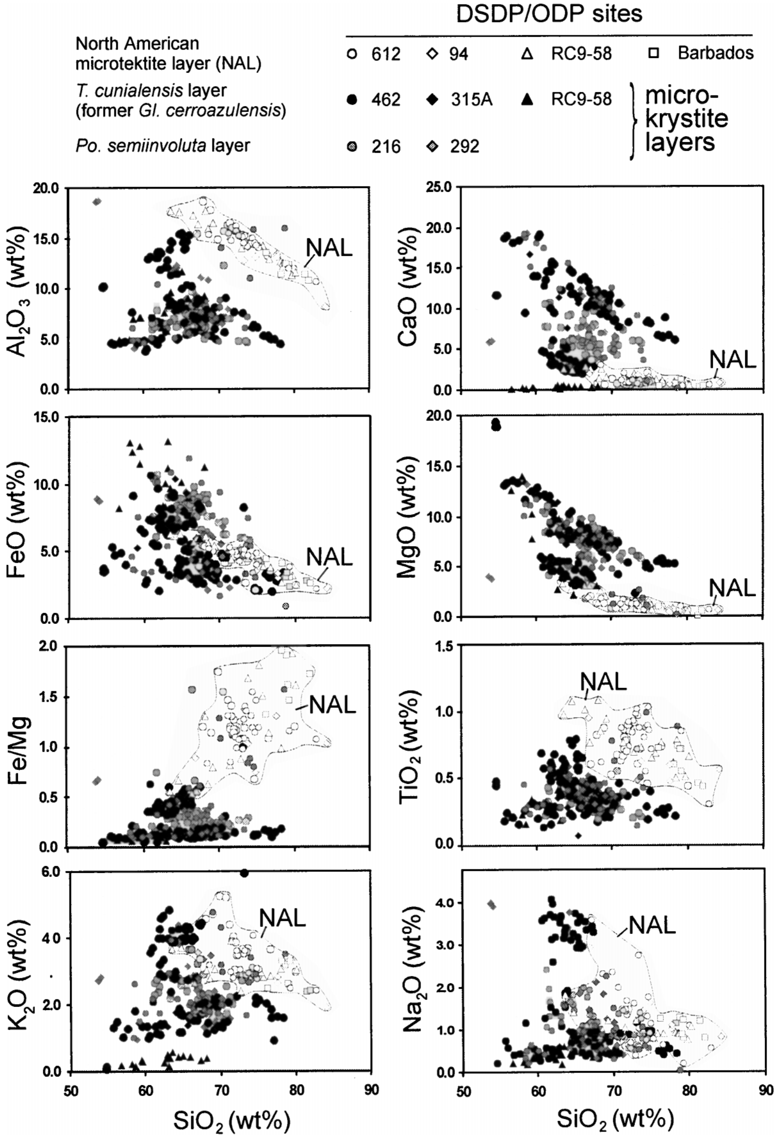

Figure 4. Major-element compositions of microtektites and microkrystites from ODP and DSDP cores. One hundred thirty-nine existing analyses are from D'Hondt, Keller, and Stallard (1987), Stecher and others (1989) and Koeberl and Glass (1988) and 189 new analyses are from this study.

the ejecta glass compositions should not be assumed a priori to have remained unchanged since deposition. Although the upper Eocene ejecta are unpalagonatised and dissolution, though locally present (Whitehead and others, 2000), is relatively uncommon, low electron microprobe totals indicate hydration by up to 9 wt.% water. The North American tektites are found on land and in ocean sediments and can thus be used to assess the effects of their interaction with pore waters of different compositions. Although they likely have a common source, the marine and terrestrial tektites have similar, but not identical compositions. The marine microtektites contain an average of 5 wt.% less SiO_2 than their terrestrial equivalents, and higher contents of all the other oxides except Na_2O. This can be explained by (1) the depletion of SiO_2 and enrichment in the other oxides (though notably not Na_2O) in the marine microtektites by saltwater interaction; and(or) (2) the enrichment of SiO_2 in the terrestrial tektites by meteoric waters while the other oxides, with the exception of Na_2O have been leached; or (3) their origin from slightly different mixes of the target rocks at Chesapeake. In the absence of an expected enrichment in the Na_2O content of glasses in the ejecta glasses in the marine sediments, or leaching of Na by Na-poor meteoric waters in the terrestrial glasses, we deem option (3) more tenable. It should be noted that all the microtektites and microkrystite populations being compared in this study were extracted from marine sediment. As such, if elemental exchange with marine pore water has occurred, they can be assumed to have experienced similar exchanges that will not selectively enrich or deplete the elemental composition of one population over another, though original subtle compositional contrasts could become clouded. Finally, it should be noted that the compositions of upper Eocene mafic microkrystites, including the more volatile and mobile oxides, are identical to impact melt rocks in the Popigai impact structure from which they were ejected (Whitehead and others, 2000). This equivalence supports our conclusion that alteration of these microkrystites by marine pore waters was minimal or absent, and also suggests that selective volatilisation of the more volatile oxides did not occur.

DISCRIMINANT ANALYSIS

To complement both individual comparisons of mean oxide percentage levels (boxplots, *t* tests, confidence intervals, and ANOVAs) and MANOVA, we propose the use of Discriminant Analysis. Both individual comparisons and MANOVA are incomplete, with individual comparisons not taking into account the orientation of the data points into multidimensional space, which is governed by the covariance matrix, and a MANOVA analysis[4] failing to report on the degree of difference

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[4] Notwithstanding associated confidence regions for the compositional mean vectors μ_i.

between the mean vector compositions, nor indicating the practical significance of such differences.[5]

We wish to advocate the use of discriminant analysis when comparing two or more sets of oxide weight percentage data because it

(a) incorporates whichever combinations of oxides seemingly best discriminate between the populations; and
(b) involves validation and the determination of probabilities of misclassification, which quantifies the (estimated) distances between the populations.

In the context of this work, discriminant analysis aims to separate distinct geochemical populations of impact ejecta. It attempts to produce a set of functions of the original variables that best discriminates between the different populations. One of the appealing aspects of discriminant analysis is that one can obtain (with the probabilities of misclassification) a meaningful numerical measure that is the predictive ability or, in other words, the percentage of correctly classified observations. This can be done using the data from which the discriminant functions were derived or, more ideally, by validating the discriminating procedure using an independent set of data for which the true classifications are known. Thus, if two populations are very different in their mean compositions, we would expect the discriminating procedure to perform well, while if, at the other extreme, there existed little or no mean compositional difference, we would expect the discriminating procedure to perform little or no better than classification at random. We give a nontechnical summary, but refer interested readers to Anderson (1984), Johnson and Wichern (1992), or Wang and Zhang (1992) for additional details.

Here is a brief summary of how discriminant analysis works in the context of our study.

(i) For a given set of oxides, a classification rule can be devised, which assigns any given compositional analysis to one of the three proposed ejecta layers. We can assess the efficiency of the classification rule by the number of compositional analyses for which it correctly interprets the actual source layer that was sampled. More specifically, for a compositional analysis O, the classification rule will produce estimates of the probabilities $p_i = P$ (compositional analysis O belongs to layer i given the data), which may be used for the predictive assignment.
(ii) An optimal classification rule[6] can then be obtained, which maximizes the ability to “discriminate” between samples drawn from distinct layers. From a practical point of view, one issue involves which subset of oxides

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[5] A well established measure of distance between two populations, which plays a role in discriminant analysis, is the Mahalanobis distance defined as $(\mu_1 - \mu_2)'\Sigma^{-1}(\mu_1 - \mu_2)$ where the covariance matrices are equal to Σ. Aitchison (1992) discusses measures of compositional difference.

[6] These rules can be of different form such as linear or quadratic.

are contributing most to the predictive ability of the model.[7] Comparing how different subsets of the oxides perform can be quite informative. We also note that it is advantageous to discard oxides that do not augment significantly the predictive ability of the classification rule for they will likely inhibit the performance of the classification rule when applied to an independent data set.

(iii) Since the same compositional analyses are used for the dual purpose of constructing an optimal classification rule as well as estimating the probabilities of misclassification, these probabilities will typically be overestimated. A remedy for this is cross-validation, which consists of systematically removing one geochemical analysis at a time, and assessing whether the removed analysis is assigned to the actual sampled layer or not based on a classification rule that is derived using all the analyses except the one removed. A perhaps more attractive alternative is to test the classification rule on an independent data set. This opportunity arises in our work with two independently drawn data sets:[8] the new major-element data from this study, and the existing analyses compiled from D'Hondt, Keller, and Stallard (1987), Koeberl and Glass (1988), and Stecher and others (1989).[9]

STATISTICAL ANALYSIS

To expand upon the factor analysis of D'Hondt, Keller, and Stallard (1987), we have performed a number of statistical comparisons of the major-element data for microtektites and microkrystites using the 139 existing data, our 189 new measurements, and a merged compilation of the two data sets. The techniques we have applied include MANOVA, ANOVA, boxplots, confidence intervals for differences between mean oxide contents, and linear discriminant analysis. Our analyses below were performed using the seven most abundant oxides (SiO_2, Al_2O_3, FeO, MgO, CaO, Na_2O, and K_2O), as well as using oxide data that had been recalculated according to logratios (i.e., $\log[Al_2O_3/SiO_2]$, $\log[FeO/SiO_2]$, ...) as suggested by Aitchison (1986) for compositional data. However, we found that there were no significant differences in the results between these two data sets and consequently, for clarity, we present only the results and interpretations based on the untransformed data.

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[7] There are several algorithms available to make this selection, such as those that are "stepwise" (see Wang and Zhang, 1992).

[8] Hereafter referred to as new, and existing.

[9] The compiled analyses from these latter two references are from the North American ejecta layer alone. Hence, the comparisons presented below pertaining to the two microkrystite layers are based solely on the data set of D'Hondt, Keller, and Stallard (1987) and our new data set.

The results of the MANOVA analyses indicate that differences exist between all three proposed layers. The difference between the North American layer (NAL) and the microkrystite layer(s) is clearly shown by the boxplots shown in Figure 5. Although the two proposed microkrystite layers are also distinct from one another according to the MANOVA results, the boxplots show that the observed difference between these two proposed layers is small. Univariate analyses performed on the two proposed crystal-bearing layers may reveal which oxides differ significantly enough between the two crystal-bearing layers to have generated the difference indicated by the MANOVA. The analyses were calculated twice: for the two microkrystite layers alone (2-sample *t* tests), and for the two microkrystite layers combined with the NAL data (ANOVA analyses). The results of the ANOVAs for the three layers (Table 1) demonstrate that all the major-element oxides, with the exception of Na_2O, can be used consistently to distinguish the NAL from the microkrystite layers. The results of the 2-sample *t* tests (Table 2) indicate that the two microkrystite layers differ from one another only in that

(a) the data of D’Hondt, Keller, and Stallard (1987) suggest that the SiO_2 contents of the *semiinvoluta* layer are slightly higher than those of the *cunialensis* layer (which is not confirmed by our new data) (Fig. 6(a) and (b));
(b) FeO contents differ between the two layers for both the existing data and our new data. Interestingly, the FeO contents of the microkrystites of analyses previous to this study are higher in the *cunialensis* layer, while the *semiinvoluta* layer microkrystites contain higher FeO according to our new data (Fig. 6(b) and (c)). The observed difference in the FeO contents of these two data sets cancel out in the merged data set (Table 1; Fig. 5(e)), for which no statistical difference is noted between the two proposed layers; and
(c) there are small differences in CaO and Na_2O contents for either the existing data or the new data in this study. (These differences are attenuated; and not significant at the 5% significance level in the merged data sets (Table 1; Fig. 6(e) and (f)).

The MANOVA results initially support the assertion of D’Hondt, Keller, and Stallard (1987) that the two microkrystite layers are geochemically distinct, although the magnitude of the difference is not established using their technique. The 2-sample *t* analyses indicate that the difference between the *cunialensis* and *semiinvoluta* microkrystite layers implied by the MANOVA analysis can be largely attributed to their slightly differing SiO_2 contents.

Various discriminant analyses were performed, of which the most noteworthy are presented below. These include

1. analyses that are either restricted to the two microkrystite layers, or analyses that involve the two microkrystite layers as well as the NAL;

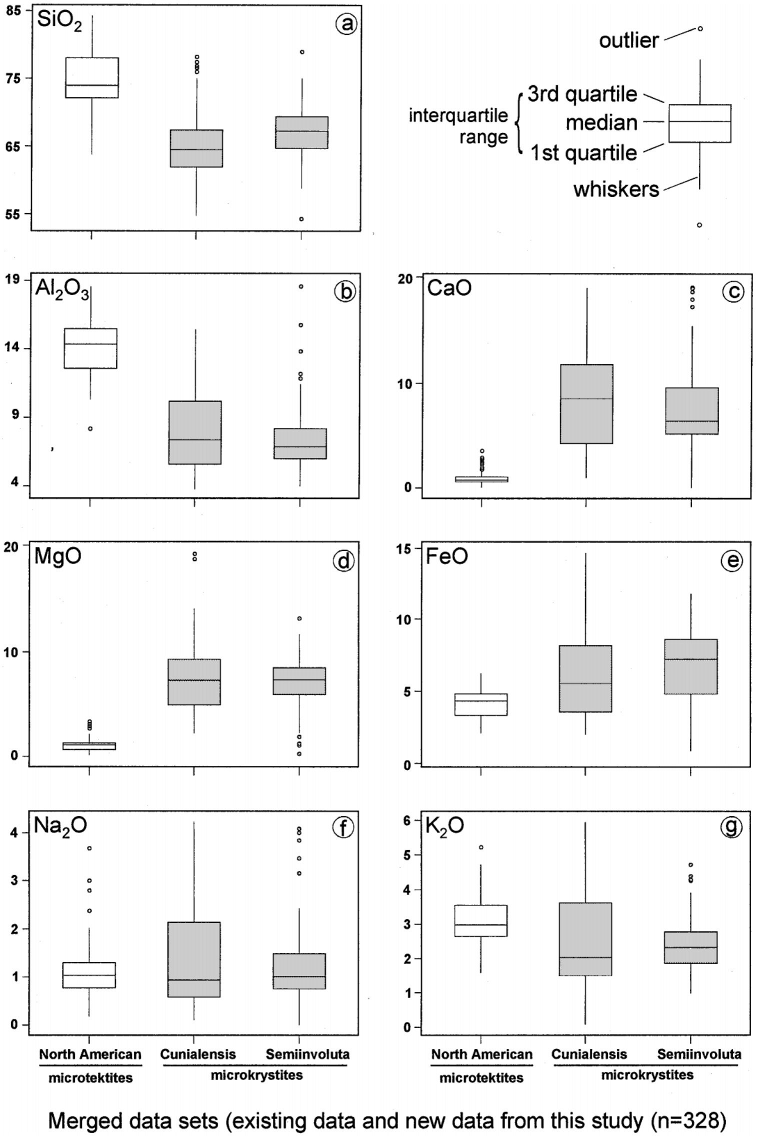

Figure 5. Box plots displaying the compositional range of microtektites (white boxes) in the North American strewn field and microkrystites (grey boxes) from the *T. cunialensis* and *Po. semiinvoluta* layers for the amalgamated data from D'Hondt, Keller, and Stallard (1987) and this study. The boxes enclose the interval between the first and third quartiles. The whiskers extend from the edges of the box to the furthest actual value within 1.5 times the interquartile range. Outliers are data points that lie outside the range of the maxima and minima of the whiskers.

Table 1. A Summary of the Results of the ANOVA and 2-Sample Comparisons Involving the Mean Compositions of the Oxides of Microtektites From the North American Layer (NAL), the *Po. semiinvoluta* (Semi) and *T. cunialensis* (Cuni) Microkrystite Layers (MKL)

	All three proposed layers (ANOVA results)			Two microkrystite layers (MKL) only (2-sample compositional analysis results)		
Oxide	Existing data ($n = 139$)	This study ($n = 189$)	Merged data ($n = 328$)	Existing data ($n = 139$)	This study ($n = 189$)	Merged data ($n = 328$)
SiO_2	*a*	*a*	*a*	*b*		*b*
Al_2O_3	*a*	*a*	*a*			
FeO	*c*	*d*	*e*	*f*,*g*	*b*,*g*	
MgO	*h*	*h*	*h*			
CaO	*h*	*h*	*h*		*f*	
Na_2O	*i*		*j*	*f*		
K_2O	*k*	*a*	*a*			
TiO_2	*a*	*a*	*a*			

Note. The results are augmented with interpretations derived from the boxplots (Figs. 5 and 6). Unless the footnotes state otherwise, there is insufficient evidence to conclude that the mean compositions of the layers differ at the 5% significance level. The confidence intervals are based on the standard 2-sample methodology and are reported with a confidence coefficient of 95%.

[a] The NAL values are much higher than those of the MKL.

[b] The two MKL means differ significantly, with $\bar{x}_{\mathrm{semi}} > \bar{x}_{\mathrm{cuni}}$. For the SiO_2 merged data set, $p < 0.001$ and $\mu_{\mathrm{semi}} - \mu_{\mathrm{cuni}} = 1.77 \pm 1.19\%$.

[c] Significant differences with $\bar{x}_{\mathrm{cuni}} > \bar{x}_{\mathrm{semi}} > \bar{x}_{\mathrm{NAL}}$.

[d] Significant differences with $\bar{x}_{\mathrm{semi}} > \bar{x}_{\mathrm{cuni}}$ and $\bar{x}_{\mathrm{semi}} > \bar{x}_{\mathrm{NAL}}$.

[e] Significant differences with $\bar{x}_{\mathrm{NAL}} < \bar{x}_{\mathrm{cuni}}$ and $\bar{x}_{\mathrm{NAL}} < \bar{x}_{\mathrm{semi}}$.

[f] The two MKL means differ significantly, with, $\bar{x}_{\mathrm{cuni}} > \bar{x}_{\mathrm{semi}}$. The p-value for CaO for the new data presented in this study $= 0.002$, and $\mu_{\mathrm{semi}} - \mu_{\mathrm{cuni}} = 2.04 \pm 1.11\%$. The existing CaO data for the two MKLs do not differ significantly ($p = 0.172$) but $\bar{x}_{\mathrm{cuni}} < \bar{x}_{\mathrm{semi}}$. In opposition, $\bar{x}_{\mathrm{cuni}} - \bar{x}_{\mathrm{semi}} = 0.98\%$ for the merged data set with a p-value of 0.087 (no significant difference between the layers at the 5% level).

[g] These are contradictory results. The larger number of analyses of the MKL present in this study contributes more weight in the merged data set but the results cancel out when merged.

[h] Significant differences with NAL values are much smaller and less variable than the two MKLs.

[i] Significant differences with $\bar{x}_{\mathrm{cuni}} > \bar{x}_{\mathrm{semi}}$.

[j] Significant differences with $\bar{x}_{\mathrm{cuni}} > \bar{x}_{\mathrm{NAL}}$.

[k] Significant differences with $\bar{x}_{\mathrm{NAL}} > \bar{x}_{\mathrm{cuni}}$ and $\bar{x}_{\mathrm{NAL}} > \bar{x}_{\mathrm{semi}}$.

2. analyses based on (i) the existing data, (ii) the new data, or (iii) the merger of these two data sets;
3. analyses based on various subsets of the major-element oxides.

The results in Table 2(A) relate to the 227 major-element analyses of the microkrystites only, and were calculated using the merged data set. First, we tested the potency of SiO_2 as the sole classification variable because the ANOVA results suggest that the major difference between the two proposed layers is their SiO_2 content. We tested the efficiency of the classification rule by cross-validation (as

Table 2. Linear Discriminant Analysis Results Based on Classification Rules Derived Using (a) the Merged SiO_2 Data Only and the SiO_2, CaO, Al_2O_3, FeO, and Na_2O Data for Comparison; (b and c) the SiO_2, CaO, Al_2O_3, FeO, and Na_2O Data From the Existing Data Set With Validation on Our New Data Set, and Vice Versa

	Predicted			
Actual	NAL	Semi	Cuni	% correct
(A) Classification rule defined using 227 merged data and tested with the same 227 data				
Semiinvoluta and *cunialensis* microkrystite layers only				
Variable used: SiO_2 only				
Semi		64	33	66.0
Cuni		46	84	64.6
Variables used: SiO_2, CaO, Al_2O_3, FeO, and Na_2O				
Semi		68	29	70.1
Cuni		45	85	65.4
(B) Classification rule defined using the existing data and tested with the 189 data from this study				
Variables used: SiO_2, CaO, Al_2O_3, FeO, and Na_2O				
NAL	22	0	0	100.0
Semi	1	33	33	49.3
Cuni	8	63	29	29.0
Semiinvoluta and *cunialensis* microkrystite layers only ($n = 167$)				
Semi	—	44	23	65.7
Cuni	—	57	43	43.0
(C) Classification rule defined using data from this study and tested with the 139 existing data				
Variables used: SiO_2, CaO, Al_2O_3, FeO, and Na_2O				
NAL	78	0	1	98.9
Semi	0	26	4	86.7
Cuni	4	12	14	46.7
Semiinvoluta and *cunialensis* microkrystite layers only ($n = 60$)				
Semi	—	16	14	53.3
Cuni	—	25	5	16.7

Note. Various other combinations and transformation (i.e., logratios) of the major-element oxides were investigated with similar results. Quadratic classification rules were also investigated with similar results.

described in part (iii) of the discriminant analysis section above). The classification rule only assigns 2/3 of the analyses to the correct layer (Table 2(A)). Including Al_2O_3, CaO, FeO, and Na_2O into the classification rule only marginally increases the number of correct assignments (Table 2(A)).

Testing the function with a second, independent set of data is preferable, because future researchers will want to know the reliability with which their analyses can be assigned to one of the two proposed layers. We can test this reliability here by virtue of two data sets: the existing data from the literature and our new data. We use the existing data to derive the optimum classification rule using the five oxides and then test its efficiency at assigning major-element data from our study

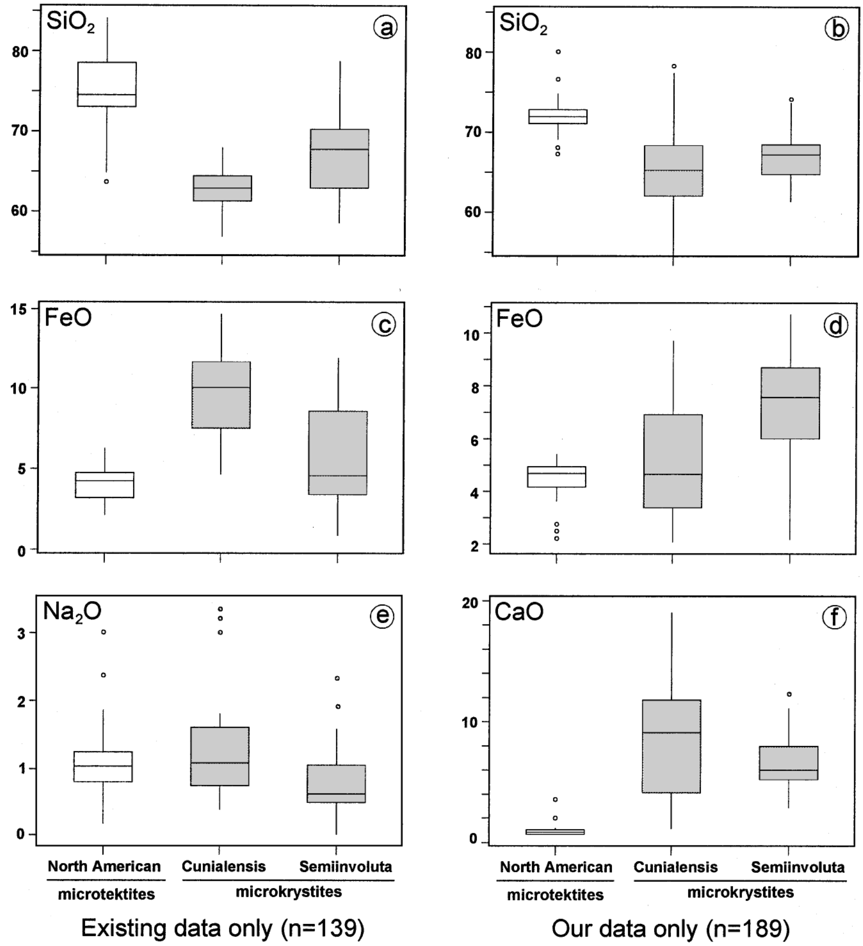

Figure 6. Box plots displaying the compositional range of microtektites and microkrystites for selected data from D'Hondt, Keller, and Stallard (1987) and new data from this study (nonmerged data). (a) and (b) display contradictory FeO data comparisons between the existing data and the new data from this study. Na$_2$O data from D'Hondt, Keller, and Stallard (1987)(c), and new CaO data from this study (d), suggest differences between the two proposed microkrystite layers, though the differences between the mean compositions are small and are not statistically significant in the merged data set.

to the correct layer (Table 2(B)). Similarly, we use our data to define the optimum classification rule, then test its efficiency using the existing data (Table 2(C)). The discriminant analysis is highly successful at correctly assigning the test group of major-element analyses for NAL microtektites: it correctly assigns 100% of our North American microtektite layer data into the NAL defined by the existing data and correctly assigns 78 of 79 of the existing NAL microtektite analyses on the basis of the field defined by our NAL data. However, the results shown in Table 2(B) and (C) demonstrate that when the discriminant function is tested with our second independent data set, the number of correct assignments of the two crystalline microkrystite layers is little better than the spin of a coin (50%).[10] These results demonstrate that although the MANOVA results indicate a difference between the two microkrystite layers, the difference is so small that it cannot be used to effectively define discriminant fields to help assign future analyzed microkrystites to one or the other of the purported microkrystite layers, that is, their difference is negligible. Consequently, on the basis of their major-element compositions, we conclude that the two proposed crystal-bearing microkrystite layers are really more similar than dissimilar, and that they likely have a common provenance. If these two proposed microkrystite layers had provenances from distinct impact structures, we would expect more distinct compositional differences reflecting compositional contrasts of the melted and ejected target rocks.

DISCUSSION AND FURTHER CONCLUSIONS

We apply a statistical methodology that employs well-established and reliable statistical techniques to compare the compositions of upper Eocene ejecta from multiple stratigraphic horizons. The methodology includes (1) first performing multivariate analysis tests, such as MANOVA on a subset of the oxide percent data; (2) determining which oxides (if any) contribute to any observed (and significant) differences between the data sets using boxplots, ANOVA and/or 2-sample comparisons; and finally (3) assessing the usefulness of any determined differences using discriminant analysis. We believe this methodology is well suited for establishing the presence/absence of useful differences between the ejecta layers in comparison with previously employed techniques, such as simultaneous R- and Q-mode factor analysis. The method is recommended for comparing sets of major-element oxide data, not only in the context of impact ejecta layers, but also in other applications. We have illustrated, with a detailed example, that valuable inferences can be made from such analyses. Although we have advocated strongly the use of such a statistical methodology when comparing sets of major-element data, we do not exclude the possibility of combining it with a simultaneous R- and Q-mode factor analysis in order to gain additional insight.[11]

A potential limitation of this study (and previous studies) resides in the possibility that the geochemical populations themselves may be nonhomogeneous,

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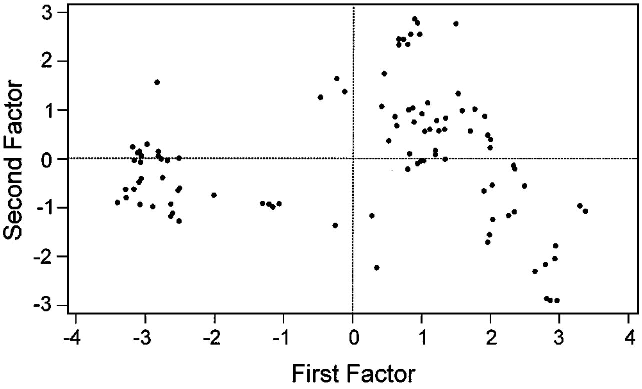
[10] This is not entirely surprising given some of the contradictory results of 2-sample *t* analyses described above (e.g., FeO).

[11] We refer to Walden, Smith, and Dackombe (1992) for a description of the advantages and limitations of simultaneous R- and Q-mode factor analysis.



Factor Loadings

	First Factor	Second Factor
SiO_2	-0.117	0.674
Al_2O_3	-0.420	0.019
FeO	-0.186	-0.524
MgO	0.431	-0.336
CaO	0.473	-0.103
Na_2O	-0.380	-0.374
K_2O	-0.470	-0.086
Cumulative total variance	0.550	0.807

Figure 7. R-mode factor analyses performed using all seven major oxides for our new data from the *T. cunialensis* layer ejecta. Note that the two clusters are distinguished on the basis of the first factor.

which makes the comparisons between ejecta layers more problematic. Although, no prior information strongly supports the assumption of homogeneity, we can study the populations themselves to gauge the reasonableness of this assumption. We performed descriptive analyses, which included R-mode factor analysis and found no evidence of highly irregular distributions, or of “clusters,” with the possible exception of two clusters within the new data collected from the *cunialensis* layer (Fig. 7). An examination of the factor loadings reveals that the presence of these clusters is largely explained by the first factor that contrasts the major element oxides CaO and MgO with a combination of the others. These two clusters may broadly reflect the composition of two slightly different, nonhomogenized melts ejected from the source crater, and which maintain some of the inhomogeneity of the target rocks. How this occurrence of clustering might affect the other statistical analyses is not entirely clear, but it should be noted that the presence of “clusters” in the *cunialensis* layer will have no effect on the success (or lack thereof) in assigning the *semiinvoluta* layer measurements shown in Table 2(B) to their correct layer.

The extent and quantity of fragmented and impact-fused target rocks ejected from an impact site are related to the impact energy and, hence, the final diameter of the impact structure. A global distribution of ejecta requires sufficiently high velocities to eject impact-shattered and molten target rocks beyond Earth’s atmosphere before it returns gravitationally, a process known as atmospheric blow-out. Melosh (1989, p. 212) has calculated that impact structures with diameters as small as 3 km are capable of producing atmospheric blow-out. However, although blow-out is possible for the smaller late Eocene impact events (e.g., Mistastin and Wanapitei), our analysis identifies only two geochemically discrete ejecta layers (the NAL and one underlying microkrystite layer). These are attributable to the

85 km diameter Chesapeake impact and the 100 km diameter Popigai impact, respectively (Poag and others, 1994; Whitehead and others, 2000). This suggests that the dispersion of the modest amounts of ejecta from the smaller impacts may not be readily identified in the sedimentary record, or that atmospheric blow-out did not occur to distribute the ejecta globally. Alternatively, ejecta from one or more of the smaller impacts may overlap with the Popigai or Chesapeake ejecta layers, but cannot be distinguished. Our results suggest that the melanocratic microkrystites from both the *Po. semiinvoluta* and *T. cunialensis* biozones possess compositions whose differences are so small that they cannot be effectively distinguished by discriminant analysis. This observation is consistent with the assertion of Glass and Burns (1987), that there is probably only one distinct microkrystite layer beneath the NAL, which implies a single impact source. Assuming the biozonation is correct, the occurrence of ejecta derived from a single impact in two separate biozones could occur if the first appearance of the index fossil on which the biozonation is based (*T. cunialensis*) was not globally synchronous. The deposition of ejecta across the oceans may thus deposit microkrystites in different biozones simultaneously.

ACKNOWLEDGMENTS

The Ocean Drilling Program generously supplied the samples for this study. This work was funded in part by an NSERC grant awarded to Eric Marchand. James Whitehead's research was supported by NSERC grants awarded to John G. Spray at UNB and Richard A. F. Grieve at the Geological Survey of Canada. We would like to sincerely thank David Lentz and Vartan Choulakian, the former for his perceptive comments on an earlier version of the manuscript, and the latter for useful discussions on multivariate data analysis techniques. Planetary and Space Science Centre contribution. Finally, we are thankful to two reviewers whose perceptive comments led to an improved presentation of our research.

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