

1 **The spatial extent of tephra deposition and environmental impacts from the 1912 Novarupta**
2 **eruption.**

3 Richard J Payne and Elías Symeonakis

4 School of Science and the Environment, Manchester Metropolitan University, Chester Street,
5 Manchester M1 5GD, UK.

6 ABSTRACT

7 The eruption of Novarupta within the Katmai Volcanic Cluster, south-west Alaska, in June 1912 was the
8 most voluminous eruption of the 20th Century but the distal distribution of tephra deposition is
9 inadequately quantified. We present new syntheses of published tephrostratigraphic studies and a large
10 quantity of previously un-investigated historical records. For the first time we apply a geostatistical
11 technique, indicator kriging, to interpolate and integrate such data. Our results show evidence for
12 tephra deposition across much of Alaska, Yukon, the northern Pacific, western British Columbia and
13 northwestern Washington. The most distal tephra deposition was observed around 2500 km downwind
14 from the volcano. Associated with tephra deposition are many accounts of acid deposition and
15 consequent impacts on vegetation and human health. Kriging offers several advantages as a means to
16 integrate and present such data. Future eruptions of a scale similar to the 1912 event have the potential
17 to cause widespread disruption. Historical records of tephra deposition extend far beyond the limit of
18 deposition constrained by tephrostratigraphic records. The distal portion of tephra fallout deposits is
19 rarely adequately mapped by tephrostratigraphy alone; contemporaneous reports of fallout can
20 provide important constraints on the extent of impacts following large explosive eruptions.

21 KEYWORDS: Tephra; Tephrostratigraphy; Cryptotephra; Volcanic Hazards; Acid deposition

23 INTRODUCTION

24 The June 1912 eruption from the Novarupta vent (58° 16' N, 155° 9' W) within the Katmai
25 Volcanic Cluster (Fig. 1) was the most voluminous volcanic eruption anywhere in the 20th century but
26 broadly typical of numerous large explosive eruptions which have occurred along the Alaska Peninsula in
27 the Holocene (Hildreth 1983; Miller & Smith 1987). The eruption lasted 60 hours with column heights in
28 three Plinian episodes reaching perhaps 26 km. The best known product of the eruption is the vast ash
29 flow of the Valley of Ten Thousand Smokes filling the valley system to the north of Novarupta and
30 comprising most of the approximately 11 km³ of ignimbrite produced by the eruption (Fierstein and
31 Hildreth 1992). Release of magma stored under nearby Mount Katmai led to the collapse of that
32 mountain forming the present caldera. Early investigators erroneously assigned the source of the
33 eruption to Katmai not Novarupta, and that name is still in widespread popular use.

34 The fall-out volume from the 1912 eruption amounted to at least 17 km³ (~6.5 km³ DRE,
35 Fierstein and Hildreth 1992) but the full spatial extent of tephra deposition is inadequately quantified
36 and we have limited knowledge of the environmental impacts of the eruption on human health and
37 ecosystems. Extensive research over recent decades has investigated the stratigraphic record of tephra
38 deposition in the vicinity of the vent and the upper Alaska Peninsula (Fierstein and Hildreth 1992;
39 Fierstein 2007; Hildreth 1983; Houghton et al. 2004). Fierstein and Hildreth (1992) present isopach maps
40 for tephra deposits greater than 10 mm thickness but it is clear that some tephra deposition occurred in
41 locations far beyond this zone (Griggs 1922). There has been no systematic attempt to map distal
42 deposition beyond the 10 mm isopach. Such thin and sparse distal tephra deposits contribute
43 comparatively little to overall eruptive volume (Fierstein and Nathenson 1992) but are important
44 because they may be associated with impacts on the environment, human health and technology. Fine
45 tephra particles can lead to significant enhancement of respiratory disease with hazards remaining for

46 considerable periods of time as tephra is disturbed and re-suspended (Hobbs et al. 1983; Martin et al.
47 2009). Newnham et al. (2010) show human health impacts from very small quantities of tephra
48 (invisible/barely visible) following the 1996 Ruapehu eruption with a significant peak in respiratory
49 mortality. Small quantities of tephra can have considerable impacts on much modern technology,
50 particularly jet engines, potentially leading to severe travel disruption as seen following the 2010
51 Eyjafjöll eruption (Brooker 2010; Davies et al. 2010). Resuspension of proximal Novarupta ash deposits
52 continues to be an aviation hazard in southern Alaska today (Hadley et al. 2004). Quantifying the extent
53 of tephra distribution provides important baseline information for tephra dispersal modelling to assess
54 such hazards. Distal impacts on ecosystems may arise through a variety of processes related to tephra
55 and volcanogenic gases/aerosols/precipitation with potential mechanisms encompassing direct toxicity,
56 abrasion, inhibition of gas exchange, acidification and indirect impacts through impacts on predators,
57 prey, parasites and pathogens (Payne et al. 2012). Palaeoenvironmental records suggest the possibility
58 of ecological impacts associated with thin or microscopic tephra layers which potentially may last for
59 decades or even centuries (Dwyer & Mitchell 1997; Kilian et al. 2006). The relationship between the
60 amount of tephra deposited and impacts on health and ecosystems is rarely simple; depending on a
61 wide variety of volcanological and environmental factors which are generally poorly understood and
62 inadequately quantified. For instance health impacts are likely to depend on particle size, mineralogy
63 and the physico-chemical properties of tephra as well as the prior health of the individuals affected
64 (Horwell and Baxter 2006) and ecological impacts upon many factors including vegetation type, soil
65 type, weather conditions and pollution status. Mapping distal tephra deposition beyond the 10 mm
66 isopach is needed as a first step towards fully understanding the impacts of this eruption and the
67 possible hazards from future eruptions.

68 Two lines of evidence can contribute to this question: the tephrostratigraphic evidence of
69 tephra in sediment cores and historical records of tephra deposition. Historical records can also provide
70 direct evidence of environmental impacts on vegetation and human health. Here we carry out an
71 extensive review of contemporary documentary sources and published stratigraphic studies and use
72 geostatistics to synthesise the results of each.

73

74 METHODS

75 We reviewed a large corpus of historical records to locate accounts of tephra deposition and
76 volcanic impacts (Online Resource 1). The most useful sources of information were found to be the
77 contemporary scientific literature (notably Griggs 1922, Martin 1913, and Kimball 1913) and newspaper
78 archives, with all the June and July 1912 issues of more than 50 titles studied. We recorded all accounts
79 of tephra-fall, acid deposition (including accounts of ‘acidic gases’ and the presumed effects of acidity)
80 and impacts on vegetation and human health. Recording of vegetation and human health impacts was
81 based on accounts consistent with known impacts such as the inflammation of eyes and lungs or
82 defoliation and discolouration of plants. Records included both those linked to volcanic activity by the
83 author and those not linked in this way; although in practise the latter were rare. For all impact types we
84 also compiled ‘absence’ locations for which we have records but which do include impacts. Most such
85 locations are where there is no mention of impacts, rather than sites where there is positive mention of
86 impacts not occurring. This is an important distinction would should be borne in mind when interpreting
87 the results.

88 In parallel, we reviewed the scientific literature on 1912 tephra and compiled locations where
89 tephra has been stratigraphically recorded. All located records were included in our analyses with the

90 exception of speculative accounts from Alberta (Hansen 1949; Horberg & Robie 1955) which are not
91 supported by geochemical data, lie a long distance beyond other stratigraphic records and are more
92 easily attributable to eruptions in the Cascade Range. Stratigraphic records of 1912 tephra rarely include
93 geochemical or petrological data, or high-precision chronologies. However, given the magnitude of the
94 eruption, the tephra's stratigraphic position near to the surface and the relative scarcity of large
95 eruptions with similar plume directions in the same time-period most of these attributions can be
96 considered reliable. We also compiled a selective list of locations where detailed tephra studies have
97 been carried out but 1912 tephra was not recorded (Online Resource 2).

98 For the distal zone, quantification of the amount of tephra deposition can be difficult. Distal
99 stratigraphic records do not always include information on the magnitude of the layer, and units vary
100 from thicknesses for visible layers to concentrations for cryptotephra, values of the latter varying by
101 sedimentary context. Historical records of tephra deposition rarely include quantitative information and
102 where they do this is often uncertain, unreliable and exaggerated. In particular it is hard to account for
103 the variability in tephra depth with drifting of unconsolidated deposits, settling over time and erosion by
104 wind and rain. Records of acid deposition and environmental impacts are almost entirely qualitative. We
105 therefore focus solely on the presence or absence of tephra deposition and impacts. It should be noted
106 that presence has a different meaning for different types of record: a greater quantity of tephra is likely
107 to be required for stratigraphic than historical recording and some tephra deposition may go
108 unrecorded by either archive.

109 There can be some uncertainty associated with both types of records. Historical events (i.e.
110 environmental damage) may be wrongly attributed to volcanic phenomena or, as many sources are
111 reporting second-hand accounts from other locations, may be simply inaccurate. It is conceivable that
112 stratigraphically recorded tephra are also mis-identified in the absence of a full suite of correlative

113 data. However, in the majority of cases there is little reason to doubt the attribution, and inclusion of
114 only those records where we can be entirely certain of presence or absence would remove the
115 overwhelming majority of data-points and reduce the mapped distribution drastically. Uncertainty is
116 particularly significant with the recording of 'absences' where stratigraphic layers may be overlooked,
117 historical events not noticed or, in both cases, simply not recorded. Our recorded absences and the
118 models based upon them, therefore show the absence of *evidence for* tephra deposition or impacts
119 rather than necessarily their true absence.

120 We apply two approaches to mapping the extent of deposition and impacts: manually with an
121 isopach line and statistically. The most distal isopachs plotted in tephra studies vary from (much) greater
122 than 10 mm down to 1 mm (e.g. Larsen et al. 2001; Kilian et al. 2003), 0.1 mm (e.g. Rose et al. 2008;
123 Watt et al. 2009) and increasingly a >0 mm isopach encompassing all identified tephra fall locations (e.g.
124 Rhoades et al. 2002; Holt et al. 2011; Matsu'ura et al. 2011). We plot such >0 mm isopach lines
125 encompassing all identified impact locations (tephra fall, acid deposition, vegetation and health impact)
126 requiring some qualitative decisions about the position and smoothing of the lines.

127 As a less subjective alternative, for the first time, we also apply the geostatistical method of
128 indicator kriging, a non-linear form of ordinary kriging (Barancourt et al., 1992; Symeonakis et al., 2009).
129 The aim of all kriging methods is to interpolate the values of a variable in an unobserved location based
130 on weighted values observed in other locations. The weights are based on the distance between the
131 measured points, the prediction locations, and the overall spatial arrangement among the measured
132 points. Kriging is unique among interpolation techniques in that it also produces estimates of the errors
133 associated with interpolated values, allowing representation of the uncertainty in the model results.
134 Indicator kriging determines, by using the measured values in the neighbourhood, the probability of

135 data values in a given area being greater than a defined threshold value (Isaaks and Srivastava 1989). It
136 makes no assumption of normality and is essentially a non-parametric counterpart to ordinary kriging.

137 In the context of this study the aim of indicator kriging is to produce a two-dimensional
138 interpolated surface representing the probability of occurrence. This involved the plotting of
139 experimental variograms from the measured presence/absence data. A number of different
140 combinations of model type (e.g. exponential, spherical, Gaussian, etc.), range, sill and nugget were then
141 tested and optimised using a leave-one-out cross validation (De Smith et al. 2009) with a focus on the
142 estimation of the range parameter. The errors derived were the root mean square error and the average
143 standard error. Given the spatial distribution of the original point data, a grid size of $2^{\circ} \times 2^{\circ}$ was chosen as
144 an appropriate size for the kriging prediction and error raster maps. For comparability we use the same
145 grid size for all interpolations despite the difference in data-set size and density. The kriging prediction
146 maps show locations where there is consistent evidence for tephra deposition or environmental impacts
147 and, on the basis of this evidence, other regions where tephra deposition or impacts are probable. The
148 maps show the probability of evidence but are not maps of the probability of tephra deposition or
149 environmental impacts *per se*: for many regions we simply have no evidence to assess whether tephra
150 may have fallen or environmental impacts occurred. One of the characteristics of kriging is its ability to
151 extrapolate beyond the known data. Where the edge of an impact zone is not confined by 'absence'
152 locations kriging will extrapolate 'presence' indefinitely but with increasing errors. Clearly such
153 extrapolation is unrealistic; we therefore apply a 'mask' limiting the kriging area to a few hundred
154 kilometres beyond the most distal data points. The positioning of this mask is a somewhat subjective
155 decision.

156

157 RESULTS

158 *Distribution of tephra*

159 Numerous historical accounts of volcanic phenomena were located from Alaska, Yukon, British
160 Columbia and Washington (Online Resource 1) and provide an indication of the movement and timing of
161 the volcanic plume (Fig. 2). Tephra deposition was first recorded from Kodiak, 170 km east of the
162 volcano in the afternoon of the 6th June 1912, continuing to the early hours of the 9th (Hildreth 1983).
163 There is little documented tephra fall west from the volcano, the most westerly records are from 158-
164 159°W at Chignik (300 km SW of Novarupta e.g. *Valdez Daily Prospector* 14/6/12) and the Innoko River,
165 reached by the 7th June (500 km NW; *Iditarod Pioneer* 15/6/12). To the north there are many records of
166 tephra falling at Fairbanks (e.g. *Fairbanks Daily News Miner* 10/6/1912) and several other records from
167 64-65°N (including Ruby: *Record-Citizen* 22/6/1912 and Tolovana: *Fairbanks Daily News Miner*
168 11/6/1912) with the most northerly of all at Rampart on the Yukon River (65.5°N, 850 km NE of
169 Novarupta; Kimball 1913). To the east of the volcano there are three records of tephra-fall in Yukon on
170 the 9th and 10th June, the most easterly at Whitehorse, 1150 km east of the volcano (135°W: *Whitehorse*
171 *Star* 14/6/12). There are numerous records from south-central Alaska including at Seward (*Seward*
172 *Weekly Gateway* 8/6/1912) and Valdez (*Valdez Daily Prospector* 13/6/12) and down the coast of south-
173 eastern Alaska (e.g. tephra fall at Juneau, 1200 km E on 8th June: *The Daily Alaska Dispatch* 11/6/1912
174 and Wrangell: Anon 1912). In these northern regions the locations of tephra records are largely dictated
175 by the distribution of population with records sparse in less populated regions such as northern and far
176 south-western Alaska. By 9th June tephra had reached Prince Rupert in northern British Columbia (*The*
177 *Daily Colonist* 11/6/1912) and by 10th had reached Victoria (*Victoria Daily Times* 11/6/1912) and
178 Vancouver, 2350 km SE of Novarupta (*The Vancouver Daily Province* 11/6/1912). There are no records of
179 tephra-fall from interior British Columbia; *The Daily Colonist* (11/6/1912) stated that 'reports from the

180 *interior indicate that no ashes are falling there'*. Tephra fell in the Puget Sound Region on 10th June with
181 records from Tatoosh Island, Olga and Port Townsend, Washington (~48°N: Kimball 1913; *Port*
182 *Townsend Leader* 11/6/1912). Port Townsend is the most southerly fall location we identify, 2400 km SE
183 of the vent. However, at Seattle it was noted that the air '*has been filled with a light mist through which*
184 *the sun shines dimly at noon... many persons are sure that the air contains volcanic dust'* (*Bellingham*
185 *Herald* 11/6/1912). Further east, there are no records of tephra fall from eastern Washington or Alberta.
186 The kriging map shows high probabilities through southern Alaska, western British Columbia and
187 western Yukon and low probabilities in Alberta, Oregon and eastern Washington (Fig. 2). The map also
188 highlights regions where probabilities are reduced due to limited and inconsistent evidence such as
189 around Yakutat in eastern Alaska. There is little evidence for tephra absence to the north or the south of
190 the mapped distribution so kriging suggests that tephra deposition in these areas is quite probable,
191 although kriging errors are increasingly large.

192 Stratigraphic records of tephra deposition are more numerous ($n = 434$) than historical records
193 ($n=60$) but most are from the proximal-medial zone with relatively few terrestrial records from southern
194 Alaska beyond the upper Alaska Peninsula and Kodiak Island. The most easterly record is from the
195 Eclipse Ice Field in southwest Yukon (Yalcin et al. 2003; 2007). There are, however, a great many records
196 of the tephra in marine cores (Nayudu 1964) which extend the tephra distribution south through the
197 Gulf of Alaska and North Pacific to 52°N and west to 163°W. Most of these marine records are
198 correlated to Novarupta solely on the basis of appearance and stratigraphic position with only a
199 minority having a well-established core chronology and even fewer having petrological or geochemical
200 data. As the Novarupta eruption was so large and with few other candidates in the recent past most of
201 these correlations can be considered secure. We are, however, suspicious of results from the most
202 westerly cores south of Cold Bay, Alaska, where the evidence does not seem to exclude other eruptive

203 sources (e.g. Pavlof Volcano). Kriging shows high probabilities of evidence across the North Pacific north
204 of 52°N with lower probabilities further south and through central Alaska (Fig. 3).

205 Combining both stratigraphic and historic evidence considerably expands the distribution
206 mapped by either line of evidence alone (Fig. 4). Taken together there is evidence for tephra deposition
207 from the southern half of Alaska, Gulf of Alaska and coastal strip of southeast Alaska and British
208 Columbia. The plume is mapped as extending primarily southeast from the vent, consistent with
209 prevailing wind directions at 5.5 km altitude (Fierstein and Hildreth 2001). Kriging shows reduced
210 probabilities in the eastern Gulf of Alaska where there is a gap between the coastal historical records
211 and eastern-most marine stratigraphic records. In some regions kriging highlights conflicts between
212 stratigraphic and historical evidence such as in southeast and central Alaska where there is no
213 stratigraphic evidence for the tephra but historical records do exist. In the extreme southeast of the
214 distribution historical records of tephra deposition in the Puget Sound region lie closely adjacent to
215 cores which Nayudu (1964) records as containing no tephra. Such results highlight the differing nature of
216 the two lines of evidence, particularly the greater sensitivity (but greater uncertainty) of historical
217 recording.

218

219 *Environmental impacts*

220 Our corpus of historical accounts contains records of acid deposition or its presumed impacts in
221 23 locations through southern Alaska, western British Columbia and northwestern Washington with
222 most clustered in south-central Alaska (Fig. 5). In four locations (Cordova, Latouche, Juneau and Valdez,
223 Alaska) historical records refer to chemical analyses of tephra or rainwater carried out to demonstrate
224 the presence of acidity. Most records are more qualitative, for instance '*Tools left lying around were*

225 *badly rusted by the sulphur in the atmosphere from the recent eruption of Mount Katmai* (Chitina
226 Leader 29/6/1912) and *'At the Ford garage on Prespect street the brass and nickel work on all of the*
227 *machines was found to be badly discolored. Some of the metal was brightened but within a few minutes*
228 *it was tarnished again. It is the belief that the air is highly charged with sulphuric acid gas, coming from*
229 *the volcanoes on the Alaskan peninsula*' (The Bellingham Herald 10/6/1912). Kriged probabilities are
230 highest in south-central Alaska constrained by absences further north, and are also elevated in the
231 Puget Sound region.

232 Associated with the records of tephra and acid deposition are descriptions of impacts on
233 vegetation ($n = 10$; Fig. 6) and human health ($n = 9$; Fig. 7). These records are less numerous and their
234 interpretation more ambiguous, but provide an impression of what the biological consequences of the
235 eruption may have been. Most references to human health impacts refer to relatively minor symptoms,
236 consisting of irritation to the skin, eyes, nose and throat. For instance, at Cordova, Alaska: *'The water*
237 *mixing with the ash in the air formed sulphuric acid which burned painfully whenever it came in contact*
238 *with the unprotected parts of the bodies of persons in the street. Before the cause was realized many*
239 *persons received painful burns in the eyes, although none was seriously injured*' (Griggs 1922) and *'There*
240 *also seemed to be much acid in the air and many persons complained of their eyes and cheeks smarting.*
241 *This was particularly true on Monday, when the falling rain carried with it a stinging effect when it*
242 *touched one's person*' (Chitina Leader 15/6/1912). Health impacts are only recorded in southern Alaska
243 with kriged probabilities constrained by absences further north in Alaska and through Canada and the
244 contiguous USA (Fig. 8). Impacts on vegetation consist primarily of accounts of discoloration of leaves
245 and defoliation. For instance, at Katalla, Alaska: *'The gardens have been very much affected as berries*
246 *and vegetation seem to be dying*' (Chitina Leader 15/6/1912) and at Latouche, Alaska: *'Acid rain did*
247 *serious injury to plants, the tender annuals of the garden were completely destroyed and the leaves of*

248 *many of the native perennial plants were so burned that they dropped off* (Griggs 1922). Impacts on
249 vegetation are mostly recorded in south-central Alaska with the exception of a single account from Port
250 Townsend, Washington, 2000 km beyond other records. This account reports that a *'lady residing on the*
251 *hill in this city reports that three of four of her roses in bloom on a bush in the yard had changed color*
252 *and were almost white, they having been partially bleached by the sulphuric acid in the air'* (Port
253 Townsend Leader 14/6/1912). Such an account is consistent with what might be expected from a
254 volcanic impact, but clearly it is impossible to exclude many other possible causes. Indicator kriging
255 predicted values are highest in south-central Alaska; the single record from Washington does not lead to
256 higher probabilities in this region due to many contradictory data points.

257

258 DISCUSSION

259 *Comparison of mapping techniques*

260 For the first time we apply geostatistics to the mapping of tephra deposition and environmental
261 impacts providing an opportunity to compare these results to those of a more conventional approach
262 using an >0 mm isopach for tephra and equivalent lines for environmental impacts. The geostatistical
263 approach seems to have several advantages. Kriging allows for a more nuanced reporting of the
264 evidence. For instance, in plotting a >0 mm isopach with the combined data (Fig. 4) it is rational to show
265 a dispersal axis in an approximately ESE direction across the Gulf of Alaska; kriging however highlights
266 that while deposition remains probable in the eastern Gulf of Alaska there is less evidence for this region
267 so probabilities are reduced and errors greater. Kriging also reduces the effect of outliers. For instance
268 uncritically plotting a line encompassing all historical records of vegetation impacts includes the outlying
269 data point from Port Townsend, Washington (Fig. 6), but kriging down-weights this point given the

270 absence of any similar records from nearby locations. While there may be reason to believe this account
271 the kriging results highlight how inconsistent this data point is with those from the surrounding area.
272 Kriging avoids the need for sometimes difficult qualitative judgments on the position of isopach lines.
273 For instance with the historical tephra data (Fig. 2) there are few historical records from the sea so a
274 decision needs to be made on how close to the coast the southern limit should be drawn; a line drawn
275 cutting directly across the Gulf of Alaska would encompass a much greater area than that shown here.
276 By fully incorporating absence as well as presence data our kriging results allow the potential for
277 meaningful extrapolation, showing for instance that despite the lack of stratigraphic studies, tephra
278 deposition in northern Alaska is quite probable, whereas considerable tephra deposition south of 50°N
279 is much more unlikely given the absence of tephra in many marine cores (Fig. 4). Kriging area estimates
280 cannot be directly compared to line plotting but suggest a broader distribution for all account types
281 (Table 1).

282 Geostatistical analyses offer more objectivity and rigour than a qualitative approach but cannot
283 replace expert judgment. A case in point is the stratigraphic records of tephra from near Cold Bay Alaska
284 (mentioned above) where we are suspicious of Novarupta attribution based on the published
285 information. Here the indicator kriging prediction values alone do not show any cause for concern.
286 There are also difficulties in defining the extent to which extrapolation is justifiable. We opt for a mask,
287 confining predictions to a reasonable distance beyond the most distal records. The positioning of this
288 mask and the selection of grid size, require some subjective judgments and partially undermine the
289 objectivity which is one of the key advantages of the kriging approach when it comes to the calculation
290 of deposition areas. As errors increase with increasing distance from the data points an alternative to
291 the mask might be to specify a maximum error level, thereby obviating the need for such a judgment
292 call. As with all statistical techniques, errors are greater with very small data sets. In the cases of

293 vegetation and health impacts it is arguable that kriging results add little information. Kriging should be
294 a useful addition to the suite of techniques used for tephra mapping but may be best used in parallel
295 with more conventional approaches.

296

297 *Tephra deposition*

298 Our extensive compilation of newly investigated historical records shows tephra deposition
299 over a much greater area than the previously mapped 10 mm isopach (Fierstein and Hildreth). Indicator
300 kriging suggests a zone of greater than 50% probability of tephra deposition based on both historical and
301 stratigraphic evidence of perhaps greater than 6,000,000 km² (Fig. 2; Table 1). In this study we
302 concentrate on presence/absence data and use indicator kriging to interpolate probabilities of
303 occurrence; our results do not directly provide information on the volume of tephra this area
304 represents. However, if we were to assume a consolidated tephra depth of 0.1 mm across the entire
305 area –which seems a reasonable assumption based on the historical records- we would arrive at a
306 (highly approximate) volume estimate of 0.2 km³ based on the isopach (0.6 km³ based on kriging P>0.5).
307 Such volumes are minor compared to the total ~17 km³ but still represent substantial quantities of
308 tephra. Where quantitative data is available it would be possible to apply ordinary kriging to interpolate
309 tephra depth (or concentration); which might offer a new approach to the calculation of eruption
310 volumes.

311 Both historical and stratigraphic records will under-estimate the full extent over which some
312 tephra may have been deposited. Following the 1912 eruption increased atmospheric opacity was noted
313 throughout the northern Hemisphere (Kimball 1913; Volz 1975); primarily representing stratospheric
314 aerosol but probably including a minor tephra component. Tiny tephra particles (<10 μm) in the

315 atmosphere may have been dispersed through much of the northern hemisphere and will certainly have
316 been deposited over a broader region than mapped here. Novarupta sulphate has been found in the
317 Greenland ice cores; there are currently no records of Novarupta tephra but the presence of
318 cryptotephra certainly cannot be excluded (Zielinski et al. 1994). Our focus is on tephra deposition
319 capable of causing impacts on the environment and modern human life. Given evidence for impacts on
320 human health and the environment associated with very small quantities of tephra (discussed in the
321 introduction) we propose that if tephra deposition is sufficient to be observable to the human eye or
322 detectable in a sediment core it may also, conceivably, be associated with such impacts.

323 Indicator kriging prediction maps based on historical and stratigraphic data suggest relatively
324 different distributions with stratigraphic records concentrated over the Gulf of Alaska and historical
325 records covering a broader region extending further north and east. The principal causes of this
326 difference are the (inevitable) scarcity of marine historical records and the greater scale of deposition
327 necessary for stratigraphic compared to historical observation. Since tephra deposition from most
328 Alaskan eruptions is only known from the stratigraphic record our results suggest that observable tephra
329 fall may have occurred over a much greater region than is generally recognised. Our results provide a
330 guide to where future tephrostratigraphic studies are required and data with which model outputs can
331 be compared. Cryptotephra may extend the stratigraphically defined limits of tephra deposition but will
332 not necessarily extend this as far as historical observations. Historical records are a valuable and often
333 under-utilised source of information on volcanic impacts. While scientists are understandably suspicious
334 of the qualitative nature of historical evidence the level of information which such records can provide
335 often exceeds that obtainable in the palaeoenvironmental record. We believe that the systematic
336 treatment of historical data can produce useful results.

337 *Volcanic hazards*

338 Within five days the Novarupta eruption had deposited tephra over a vast area of NW North
339 America with observable tephra deposition as far away as Port Townsend, Washington, almost 2500 km
340 from the volcano. Associated with this tephra deposition are records of acid deposition and impacts on
341 vegetation and human health which provide an indication of the biological impacts of the volcanic
342 products. Our results suggest the possibility for inhalation of tephra and gases to have exacerbated
343 respiratory conditions. Although the eruption has not been directly linked to any deaths it may have
344 more widely reduced 'life years' by exacerbating other conditions, particularly lung complaints
345 (Gudmundsson 2011). Our results do not suggest wide-spread mortality, but it is entirely possible that
346 additional deaths did occur but were not linked to volcanic activity due to a lack of knowledge of the
347 possible impacts of inhaling volcanic products. Investigation of the fragmentary demographic and
348 medical records from 1912 would prove useful.

349 Impacts on vegetation are difficult to determine based on these historical records alone but
350 there is evidence for moderately severe, although possibly localised, impacts with accounts reminiscent
351 of those following the 1783 Laki eruption in north-western Europe (*cf* Grattan & Charman 1994). In
352 these accounts, more than any others there is a risk of exaggeration. Descriptions immediately following
353 the eruption such as '*it has ruined all the vegetation within five hundred miles of its base on all sides*'
354 (Whitehorse Star 21/6/12) are not supported by evidence and appear over the top. However, other
355 accounts have a more measured tone and are broadly consistent with the impacts which would be
356 expected from tephra and volcanogenic acid damage. In the proximal to medial zone where vegetation
357 was buried by many centimetres of tephra, recovery was relatively rapid with much vegetation
358 establishing on, or penetrating through the tephra by the time of the National Geographic expeditions in
359 the years following the eruption (Griggs 1933). These results call for tephropalaeoecological study of the
360 ecological impacts of this, and other Alaskan eruptions.

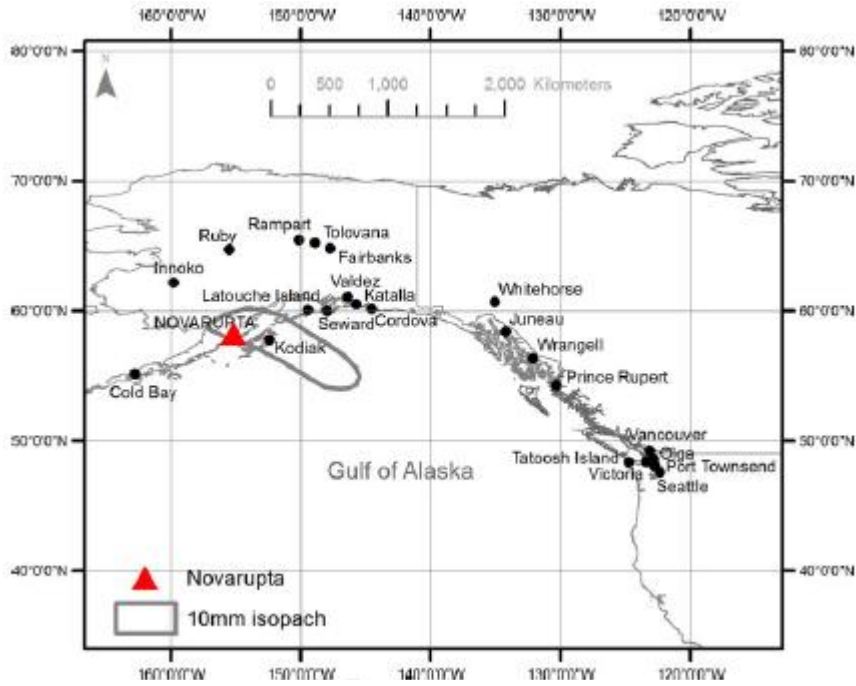
361 Novarupta serves as a good model for the potential hazards posed by future large eruptions of a
362 scale which have occurred relatively frequently in Alaska over the Holocene. Such assessments require
363 the assembly of high quality data and the use of the best available techniques to integrate and analyse
364 this data. By compiling a large corpus of impact records and introducing indicator kriging as a possible
365 tool to assess this data our study advances our understanding of Novarupta impacts and possible future
366 volcanic hazards. An eruption of similar magnitude today has the potential to i) widely disrupt
367 agriculture and fisheries, ii) impact on natural ecosystems, iii) impair communication systems, iv) cause
368 health problems, v) cause damage to a variety of machinery, potentially endangering electricity supply,
369 vi) contaminate water supplies, and vii) affect air traffic (Fierstein & Hildreth 2001). The latter might
370 have the most widespread impacts affecting both the busy trans-Pacific air corridors directly overhead
371 and potentially air traffic through much of the northern Hemisphere (Fierstein & Hildreth 2001;
372 Welchman 2010). Our results suggest that, for instance, it is very likely that if Novarupta happened
373 today it would cause the closure of airports in the western contiguous USA. The impacts of the 1912
374 eruption were limited as much of the tephra was deposited over the ocean and at the time life in the
375 region was not dependent on technology like aircraft. A future eruption of this magnitude has the
376 potential for much more widespread impacts.

377 ACKNOWLEDGEMENTS

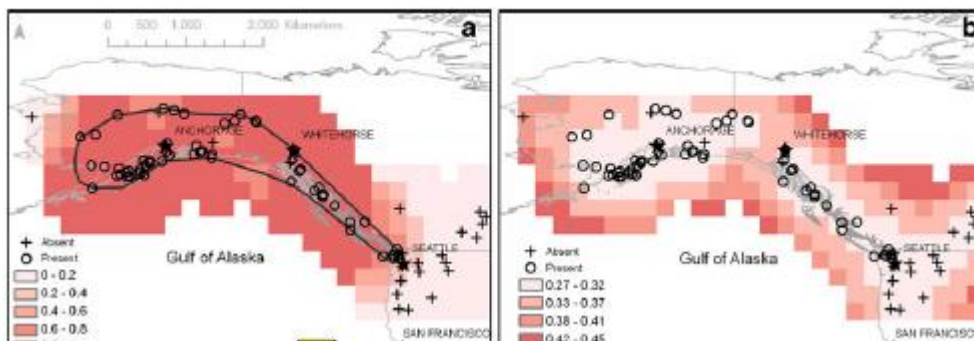
378 Grateful thanks to the numerous scientists and librarians across North America who assisted with the
379 location of relevant material and particularly to Siân Hughes of the Sir Kenneth Green Library,
380 Manchester Metropolitan University. Thanks to four reviewers and two editors for helpful and insightful
381 comments on previous versions of the manuscript. The first author would like to hear from any readers
382 with knowledge of Novarupta tephra records not included in Online Resource 1, particularly any other
383 historical records from the distal zone.

385 FIGURES

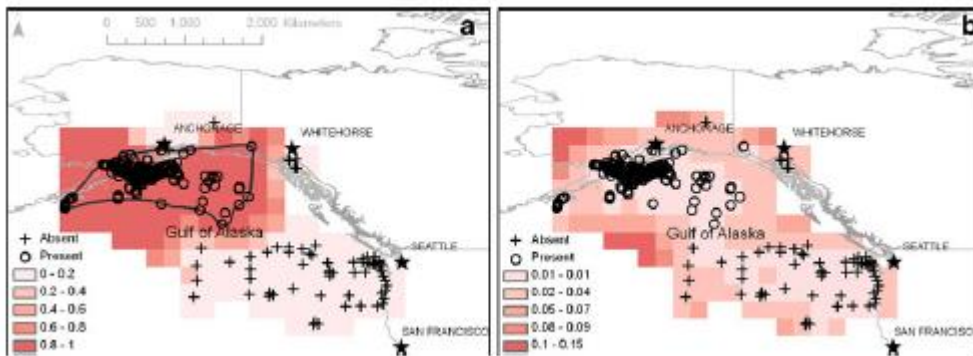
386 Figure 1. The regional situation, showing settlements referred to in the text, Novarupta and the 10mm
387 tephra isopach as plotted by Fierstein & Hildreth (1992).



388
389 Figure 2. Tephra deposition locations based on historical records for the 1912 Novarupta eruption in
390 northwest North America, showing indicator kriging predicted values (A: see text for details), and
391 respective errors (B) with line connecting most distal fall locations. Raw data in Online Resource 1 and 2.

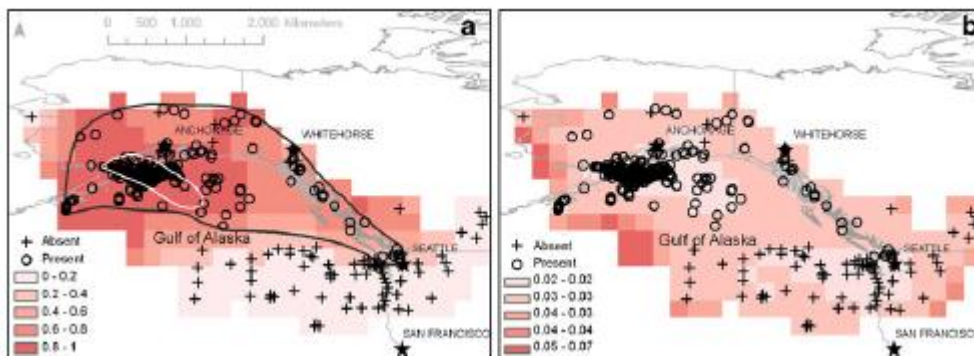


393 Figure 3. Stratigraphic tephra deposition locations, details as for Fig. 1.



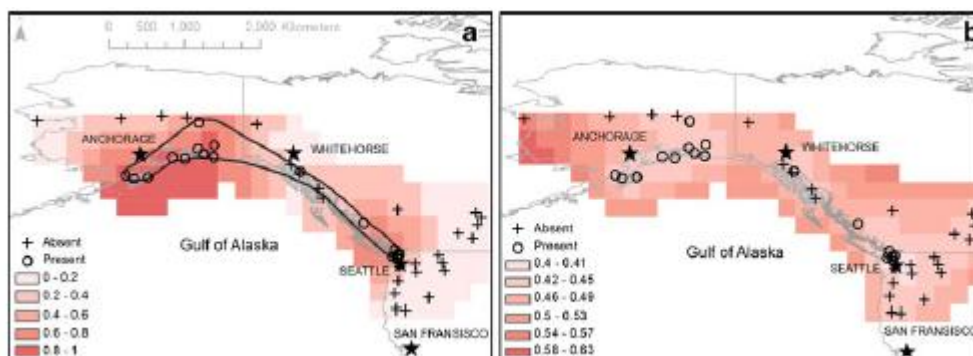
394

395 Figure 4. Tephra deposition locations combining both historical and stratigraphic information. Details as
396 for Fig. 1. White line shows 10 mm isopach as plotted by Fierstein & Hildreth (1992).



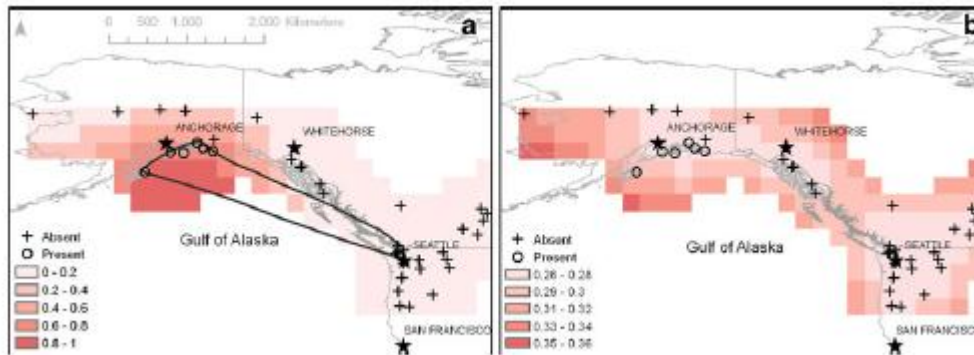
397

398 Figure 5. Acid deposition locations, details as for Fig. 1.



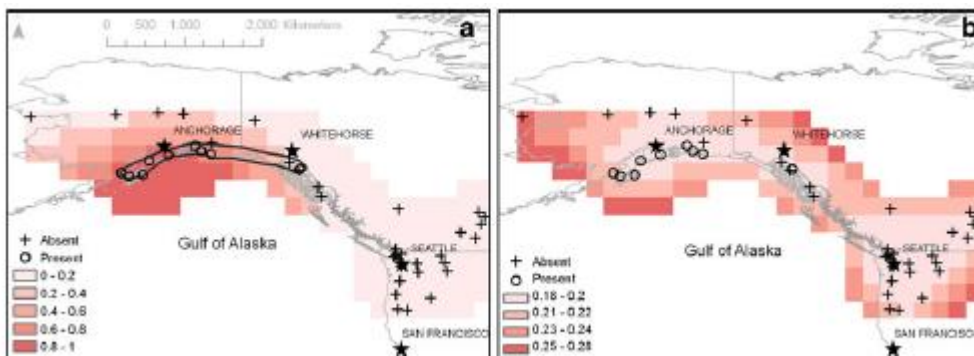
399

400 Figure 6. Vegetation impact locations, details as for Fig. 1.



401

402 Figure 7. Health impact locations, details as for Fig. 1.



403

404 Table 1. Areas of tephra deposition and environmental impacts estimated on the basis of Figures 1-6
405 using Albers equal-area conic projection. Indicator kriging results show areas with probability greater
406 than 0.5 and so are not directly comparable with line mapped area. Note that results incorporate
407 qualitative judgements about positioning of line mapped area (particularly important for vegetation)
408 and pixel size and mask positioning for kriged areas.

Evidence type	Line mapped area (km ²)	Kriging probability ($P > 0.5$ area (km ²))
Historical tephra records	1,200,000	3,800,000
Stratigraphic tephra records	810,000	2,100,000
Combined tephra records	2,500,000	6,650,887
Acid deposition records	520,000	1,331,636
Vegetation impact records	750,000	798,982
Health impact records	180,000	1,012,044

409

410 SUPPLEMENTARY MATERIAL

411 Online Resource 1. Raw data: 'presence' locations for all data types and data sources.

412 Online Resource 2. Raw data: 'absence' locations for all data types.

413

414

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