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

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ABSTRACT

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

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

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INTRODUCTION

The June 1912 eruption from the Novarupta vent (58° 16′ N, 155° 9′ W) within the Katmai Volcanic Cluster (Fig. 1) was the most voluminous volcanic eruption anywhere in the 20th century but broadly typical of numerous large explosive eruptions which have occurred along the Alaska Peninsula in the Holocene (Hildreth 1983; Miller & Smith 1987). The eruption lasted 60 hours with column heights in three Plinian episodes reaching perhaps 26 km. The best known product of the eruption is the vast ash flow of the Valley of Ten Thousand Smokes filling the valley system to the north of Novarupta and comprising most of the approximately 11 km^3 of ignimbrite produced by the eruption (Fierstein and Hildreth 1992). Release of magma stored under nearby Mount Katmai led to the collapse of that mountain forming the present caldera. Early investigators erroneously assigned the source of the eruption to Katmai not Novarupta, and that name is still in widespread popular use.

The fall-out volume from the 1912 eruption amounted to at least 17 km^3 (~6.5 km^3 DRE, Fierstein and Hildreth 1992) but the full spatial extent of tephra deposition is inadequately quantified and we have limited knowledge of the environmental impacts of the eruption on human health and ecosystems. Extensive research over recent decades has investigated the stratigraphic record of tephra deposition in the vicinity of the vent and the upper Alaska Peninsula (Fierstein and Hildreth 1992; Fierstein 2007; Hildreth 1983; Houghton et al. 2004). Fierstein and Hildreth (1992) present isopach maps for tephra deposits greater than 10 mm thickness but it is clear that some tephra deposition occurred in locations far beyond this zone (Griggs 1922). There has been no systematic attempt to map distal deposition beyond the 10 mm isopach. Such thin and sparse distal tephra deposits contribute comparatively little to overall eruptive volume (Fierstein and Nathenson 1992) but are important because they may be associated with impacts on the environment, human health and technology. Fine tephra particles can lead to significant enhancement of respiratory disease with hazards remaining for considerable periods of time as tephra is disturbed and re-suspended (Hobbs et al. 1983; Martin et al. 2009). Newnham et al. (2010) show human health impacts from very small quantities of tephra (invisible/barely visible) following the 1996 Ruapehu eruption with a significant peak in respiratory mortality. Small quantities of tephra can have considerable impacts on much modern technology, particularly jet engines, potentially leading to severe travel disruption as seen following the 2010 Eyjafjöll eruption (Brooker 2010; Davies et al. 2010). Resuspension of proximal Novarupta ash deposits continues to be an aviation hazard in southern Alaska today (Hadley et al. 2004). Quantifying the extent of tephra distribution provides important baseline information for tephra dispersal modelling to assess such hazards. Distal impacts on ecosystems may arise through a variety of processes related to tephra and volcanogenic gases/aerosols/precipitation with potential mechanisms encompassing direct toxicity, abrasion, inhibition of gas exchange, acidification and indirect impacts through impacts on predators, prey, parasites and pathogens (Payne et al. 2012). Palaeoenvironmental records suggest the possibility of ecological impacts associated with thin or microscopic tephra layers which potentially may last for decades or even centuries (Dwyer & Mitchell 1997; Kilian et al. 2006). The relationship between the amount of tephra deposited and impacts on health and ecosystems is rarely simple; depending on a wide variety of volcanological and environmental factors which are generally poorly understood and inadequately quantified. For instance health impacts are likely to depend on particle size, mineralogy and the physico-chemical properties of tephra as wealth as the prior health of the individuals affected (Horwell and Baxter 2006) and ecological impacts upon many factors including vegetation type, soil type, weather conditions and pollution status. Mapping distal tephra deposition beyond the 10 mm isopach is needed as a first step towards fully understanding the impacts of this eruption and the possible hazards from future eruptions.

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

METHODS

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

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

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

There can be some uncertainty associated with both types of records. Historical events (i.e. environmental damage) may be wrongly attributed to volcanic phenomena or, as many sources are reporting second-hand accounts from other locations, may be simply inaccurate. It is conceivable that stratigraphically recorded tephras are also mis-identified in the absence of a full suite of correlative data. However, in the majority of cases there is little reason to doubt the attribution, and inclusion of only those records where we can be entirely certain of presence or absence would remove the overwhelming majority of data-points and reduce the mapped distribution drastically. Uncertainty is particularly significant with the recording of ‘absences’ where stratigraphic layers may be overlooked, historical events not noticed or, in both cases, simply not recorded. Our recorded absences and the models based upon them, therefore show the absence of *evidence for* tephra deposition or impacts rather than necessarily their true absence.

We apply two approaches to mapping the extent of deposition and impacts: manually with an isopach line and statistically. The most distal isopachs plotted in tephra studies vary from (much) greater 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; Watt et al. 2009) and increasingly a >0 mm isopach encompassing all identified tephra fall locations (e.g. Rhoades et al. 2002; Holt et al. 2011; Matsu’ura et al. 2011). We plot such >0 mm isopach lines encompassing all identified impact locations (tephra fall, acid deposition, vegetation and health impact) requiring some qualitative decisions about the position and smoothing of the lines.

As a less subjective alternative, for the first time, we also apply the geostatistical method of indicator kriging, a non-linear form of ordinary kriging (Barancourt et al., 1992; Symeonakis et al., 2009). The aim of all kriging methods is to interpolate the values of a variable in an unobserved location based on weighted values observed in other locations. The weights are based on the distance between the measured points, the prediction locations, and the overall spatial arrangement among the measured points. Kriging is unique among interpolation techniques in that it also produces estimates of the errors associated with interpolated values, allowing representation of the uncertainty in the model results. Indicator kriging determines, by using the measured values in the neighbourhood, the probability of data values in a given area being greater than a defined threshold value (Isaaks and Srivastava 1989). It makes no assumption of normality and is essentially a non-parametric counterpart to ordinary kriging.

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

RESULTS

Distribution of tephra

Numerous historical accounts of volcanic phenomena were located from Alaska, Yukon, British Columbia and Washington (Online Resource 1) and provide an indication of the movement and timing of the volcanic plume (Fig. 2). Tephra deposition was first recorded from Kodiak, 170 km east of the volcano in the afternoon of the 6th June 1912, continuing to the early hours of the 9th (Hildreth 1983). There is little documented tephra fall west from the volcano, the most westerly records are from 158-159°W at Chignik (300 km SW of Novarupta e.g. *Valdez Daily Prospector* 14/6/12) and the Innoko River, reached by the 7th June (500 km NW; *Iditarod Pioneer* 15/6/12). To the north there are many records of tephra falling at Fairbanks (e.g. *Fairbanks Daily News Miner* 10/6/1912) and several other records from 64-65°N (including Ruby: *Record-Citizen* 22/6/1912 and Tolovana: *Fairbanks Daily News Miner* 11/6/1912) with the most northerly of all at Rampart on the Yukon River (65.5°N, 850 km NE of Novarupta; Kimball 1913). To the east of the volcano there are three records of tephra-fall in Yukon on the 9th and 10th June, the most easterly at Whitehorse, 1150 km east of the volcano (135°W: *Whitehorse Star* 14/6/12). There are numerous records from south-central Alaska including at Seward (*Seward Weekly Gateway* 8/6/1912) and Valdez (*Valdez Daily Prospector* 13/6/12) and down the coast of south-eastern Alaska (e.g. tephra fall at Juneau, 1200 km E on 8th June: *The Daily Alaska Dispatch* 11/6/1912 and Wrangell: Anon 1912). In these northern regions the locations of tephra records are largely dictated by the distribution of population with records sparse in less populated regions such as northern and far south-western Alaska. By 9th June tephra had reached Prince Rupert in northern British Columbia (*The Daily Colonist* 11/6/1912) and by 10th had reached Victoria (*Victoria Daily Times* 11/6/1912) and Vancouver, 2350 km SE of Novarupta (*The Vancouver Daily Province* 11/6/1912). There are no records of tephra-fall from interior British Columbia; *The Daily Colonist* (11/6/1912) stated that '*reports from the* *interior indicate that no ashes are falling there*'. Tephra fell in the Puget Sound Region on 10th June with records from Tatoosh Island, Olga and Port Townsend, Washington (~48°N: Kimball 1913; *Port Townsend Leader* 11/6/1912). Port Townsend is the most southerly fall location we identify, 2400 km SE of the vent. However, at Seattle it was noted that the air '*has been filled with a light mist through which the sun shines dimly at noon… many persons are sure that the air contains volcanic dust*' (*Bellingham Herald* 11/6/1912). Further east, there are no records of tephra fall from eastern Washington or Alberta. The kriging map shows high probabilities through southern Alaska, western British Columbia and western Yukon and low probabilities in Alberta, Oregon and eastern Washington (Fig. 2). The map also highlights regions where probabilities are reduced due to limited and inconsistent evidence such as around Yakutat in eastern Alaska. There is little evidence for tephra absence to the north or the south of the mapped distribution so kriging suggests that tephra deposition in these areas is quite probable, although kriging errors are increasingly large.

Stratigraphic records of tephra deposition are more numerous ($n = 434$) than historical records (n=60) but most are from the proximal-medial zone with relatively few terrestrial records from southern Alaska beyond the upper Alaska Peninsula and Kodiak Island. The most easterly record is from the Eclipse Ice Field in southwest Yukon (Yalcin et al. 2003; 2007). There are, however, a great many records of the tephra in marine cores (Nayudu 1964) which extend the tephra distribution south through the Gulf of Alaska and North Pacific to 52°N and west to 163°W. Most of these marine records are correlated to Novarupta solely on the basis of appearance and stratigraphic position with only a minority having a well-established core chronology and even fewer having petrological or geochemical data. As the Novarupta eruption was so large and with few other candidates in the recent past most of these correlations can be considered secure. We are, however, suspicious of results from the most westerly cores south of Cold Bay, Alaska, where the evidence does not seem to exclude other eruptive sources (e.g. Pavlof Volcano). Kriging shows high probabilities of evidence across the North Pacific north of 52°N with lower probabilities further south and through central Alaska (Fig. 3).

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

Environmental impacts

Our corpus of historical accounts contains records of acid deposition or its presumed impacts in 23 locations through southern Alaska, western British Columbia and northwestern Washington with most clustered in south-central Alaska (Fig. 5). In four locations (Cordova, Latouche, Juneau and Valdez, Alaska) historical records refer to chemical analyses of tephra or rainwater carried out to demonstrate the presence of acidity. Most records are more qualitative, for instance '*Tools left lying around were* *badly rusted by the sulphur in the atmosphere from the recent eruption of Mount Katmai*' (Chitina Leader 29/6/1912) and '*At the Ford garage on Prespect street the brass and nickel work on all of the machines was found to be badly discolored. Some of the metal was brightened but within a few minutes it was tarnished again. It is the belief that the air is highly charged with sulphuric acid gas, coming from the volcanoes on the Alaskan peninsula*' (The Bellingham Herald 10/6/1912). Kriged probabilities are highest in south-central Alaska constrained by absences further north, and are also elevated in the Puget Sound region.

Associated with the records of tephra and acid deposition are descriptions of impacts on vegetation (*n* = 10; Fig. 6) and human health (*n* = 9; Fig. 7). These records are less numerous and their interpretation more ambiguous, but provide an impression of what the biological consequences of the eruption may have been. Most references to human health impacts refer to relatively minor symptoms, consisting of irritation to the skin, eyes, nose and throat. For instance, at Cordova, Alaska: '*The water mixing with the ash in the air formed sulphuric acid which burned painfully whenever it came in contact with the unprotected parts of the bodies of persons in the street. Before the cause was realized many persons received painful burns in the eyes, although none was seriously injured*' (Griggs 1922) and '*There also seemed to be much acid in the air and many persons complained of their eyes and cheeks smarting. This was particularly true on Monday, when the falling rain carried with it a stinging effect when it touched one's person*' (Chitina Leader 15/6/1912). Health impacts are only recorded in southern Alaska with kriged probabilities constrained by absences further north in Alaska and through Canada and the contiguous USA (Fig. 8). Impacts on vegetation consist primarily of accounts of discoloration of leaves and defoliation. For instance, at Katalla, Alaska: '*The gardens have been very much affected as berries and vegetation seem to be dying*' (Chitina Leader 15/6/1912) and at Latouche, Alaska: '*Acid rain did serious injury to plants, the tender annuals of the garden were completely destroyed and the leaves of* *many of the native perennial plants were so burned that they dropped off*' (Griggs 1922). Impacts on vegetation are mostly recorded in south-central Alaska with the exception of a single account from Port Townsend, Washington, 2000 km beyond other records. This account reports that a *'lady residing on the hill in this city reports that three of four of her roses in bloom on a bush in the yard had changed color and were almost white, they having been partially bleached by the sulphuric acid in the air*' (Port Townsend Leader 14/6/1912). Such an account is consistent with what might be expected from a volcanic impact, but clearly it is impossible to exclude many other possible causes. Indicator kriging predicted values are highest in south-central Alaska; the single record from Washington does not lead to higher probabilities in this region due to many contradictory data points.

DISCUSSION

Comparison of mapping techniques

For the first time we apply geostatistics to the mapping of tephra deposition and environmental impacts providing an opportunity to compare these results to those of a more conventional approach using an >0 mm isopach for tephra and equivalent lines for environmental impacts. The geostatistical approach seems to have several advantages. Kriging allows for a more nuanced reporting of the evidence. For instance, in plotting a >0 mm isopach with the combined data (Fig. 4) it is rational to show a dispersal axis in an approximately ESE direction across the Gulf of Alaska; kriging however highlights that while deposition remains probable in the eastern Gulf of Alaska there is less evidence for this region so probabilities are reduced and errors greater. Kriging also reduces the effect of outliers. For instance uncritically plotting a line encompassing all historical records of vegetation impacts includes the outlying data point from Port Townsend, Washington (Fig. 6), but kriging down-weights this point given the absence of any similar records from nearby locations. While there may be reason to believe this account the kriging results highlight how inconsistent this data point is with those from the surrounding area. Kriging avoids the need for sometimes difficult qualitative judgments on the position of isopach lines. For instance with the historical tephra data (Fig. 2) there are few historical records from the sea so a decision needs to be made on how close to the coast the southern limit should be drawn; a line drawn cutting directly across the Gulf of Alaska would encompass a much greater area than that shown here. By fully incorporating absence as well as presence data our kriging results allow the potential for meaningful extrapolation, showing for instance that despite the lack of stratigraphic studies, tephra deposition in northern Alaska is quite probable, whereas considerable tephra deposition south of 50°N is much more unlikely given the absence of tephra in many marine cores (Fig. 4). Kriging area estimates cannot be directly compared to line plotting but suggest a broader distribution for all account types (Table 1).

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

Tephra deposition

Our extensive compilation of newly investigated historical records shows tephra deposition over a much greater area than the previously mapped 10 mm isopach (Fierstein and Hildreth). Indicator kriging suggests a zone of greater than 50% probability of tephra deposition based on both historical and stratigraphic evidence of perhaps greater than 6,000,000 km^2 (Fig. 2; Table 1). In this study we concentrate on presence/absence data and use indicator kriging to interpolate probabilities of occurrence; our results do not directly provide information on the volume of tephra this area represents. However, if we were to assume a consolidated tephra depth of 0.1 mm across the entire area –which seems a reasonable assumption based on the historical records- we would arrive at a (highly approximate) volume estimate of 0.2 km^3 based on the isopach (0.6 km^3 based on kriging $P>0.5$). Such volumes are minor compared to the total ~17 km^3 but still represent substantial quantities of tephra. Where quantitative data is available it would be possible to apply ordinary kriging to interpolate tephra depth (or concentration); which might offer a new approach to the calculation of eruption volumes.

Both historical and stratigraphic records will under-estimate the full extent over which some tephra may have been deposited. Following the 1912 eruption increased atmospheric opacity was noted throughout the northern Hemisphere (Kimball 1913; Volz 1975); primarily representing stratospheric aerosol but probably including a minor tephra component. Tiny tephra particles (<10 μm) in the atmosphere may have been dispersed through much of the northern hemisphere and will certainly have been deposited over a broader region than mapped here. Novarupta sulphate has been found in the Greenland ice cores; there are currently no records of Novarupta tephra but the presence of cryptotephra certainly cannot be excluded (Zielinski et al. 1994). Our focus is on tephra deposition capable of causing impacts on the environment and modern human life. Given evidence for impacts on human health and the environment associated with very small quantities of tephra (discussed in the introduction) we propose that if tephra deposition is sufficient to be observable to the human eye or detectable in a sediment core it may also, conceivably, be associated with such impacts.

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

Volcanic hazards

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

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

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

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FIGURES

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

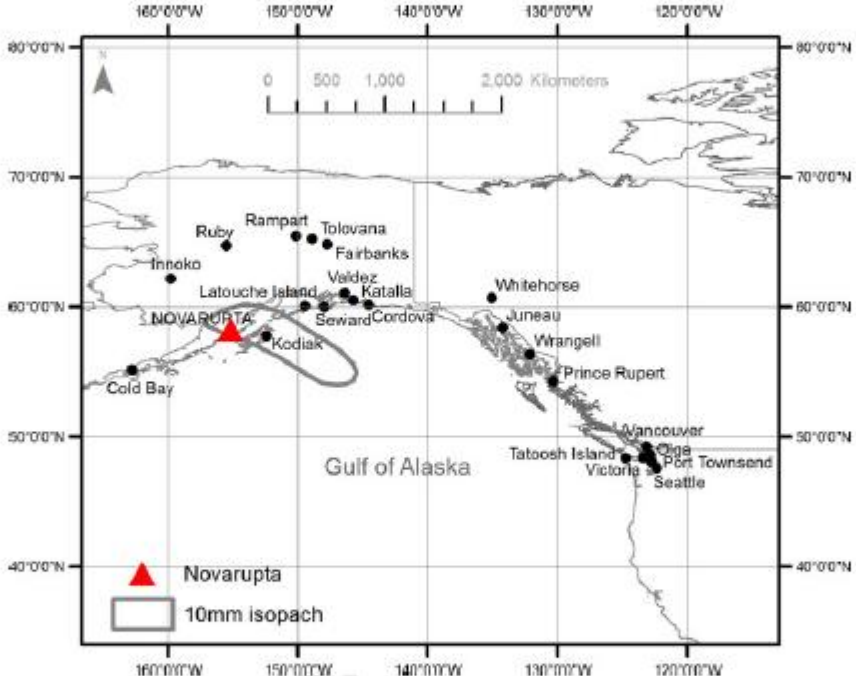


Figure 2. Tephra deposition locations based on historical records for the 1912 Novarupta eruption in northwest North America, showing indicator kriging predicted values (A: see text for details), and respective errors (B) with line connecting most distal fall locations. Raw data in Online Resource 1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

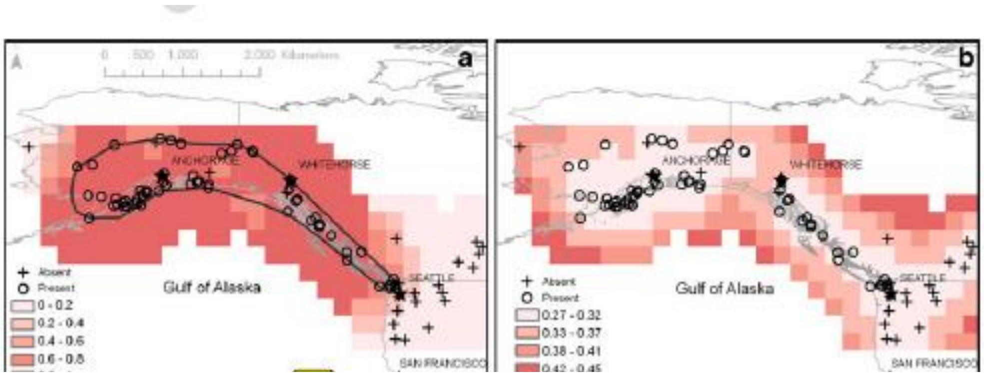


Figure 3. Stratigraphic tephra deposition locations, details as for Fig. 1.

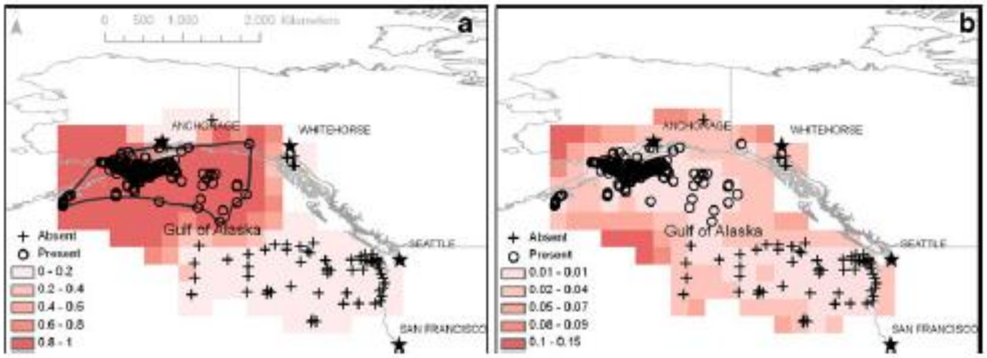


Figure 4. Tephra deposition locations combining both historical and stratigraphic information. Details as for Fig. 1. White line shows 10 mm isopach as plotted by Fierstein & Hildreth (1992).

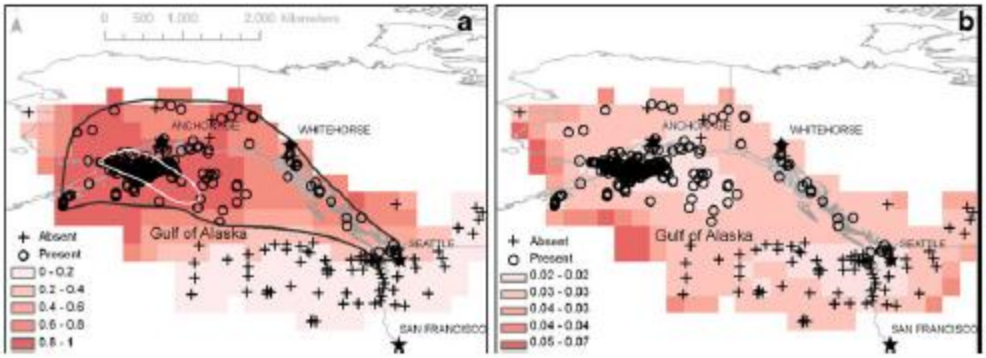


Figure 5. Acid deposition locations, details as for Fig. 1.

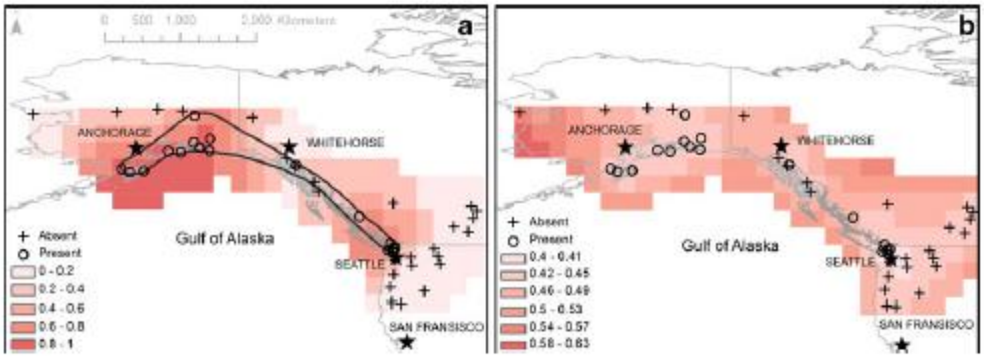


Figure 6. Vegetation impact locations, details as for Fig. 1.

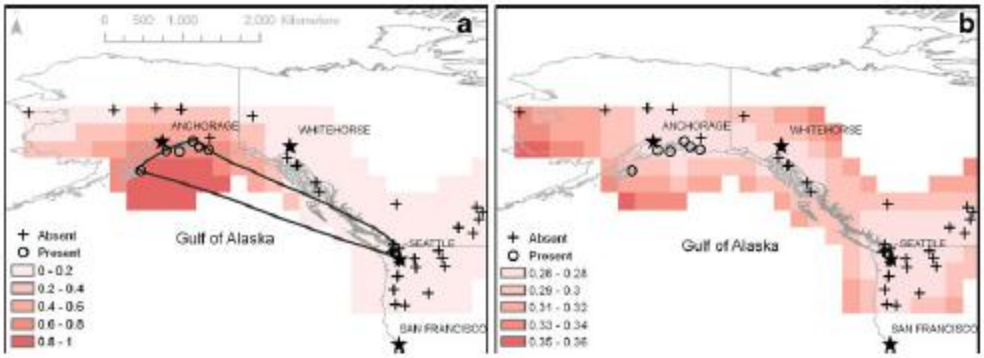


Figure 7. Health impact locations, details as for Fig. 1.

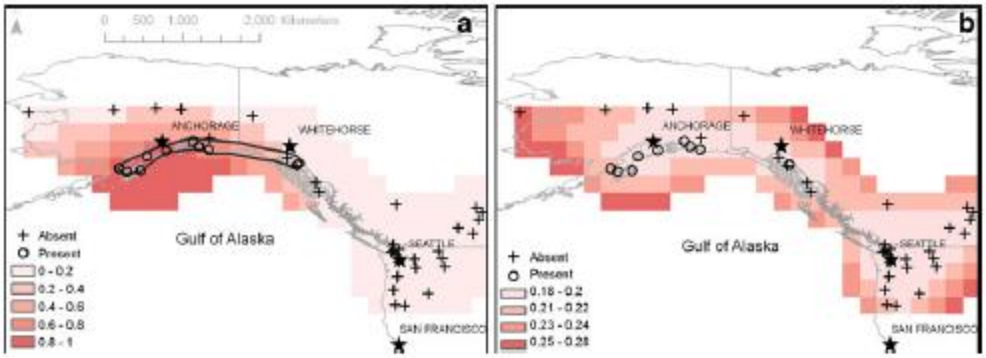
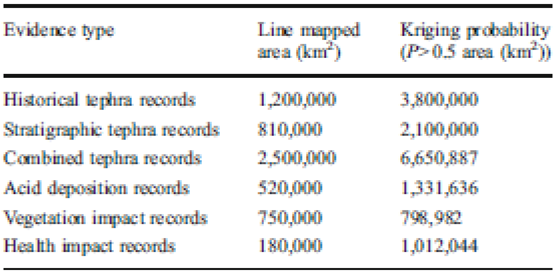


Table 1. Areas of tephra deposition and environmental impacts estimated on the basis of Figures 1-6 using Albers equal-area conic projection. Indicator kriging results show areas with probability greater than 0.5 and so are not directly comparable with line mapped area. Note that results incorporate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

SUPPLEMENTARY MATERIAL

Online Resource 1. Raw data: ‘presence’ locations for all data types and data sources.

Online Resource 2. Raw data: ‘absence’ locations for all data types.

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