Eruption Dynamics of the Inyo Crater System

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Introduction

I. Background

The three South Inyo Craters are a part of the Mono-Inyo Chain of craters that extends from Mono Lake to Mammoth mountain. In this chain, the craters in the center are the youngest while the ones on the end are the youngest. The South Inyo Craters, being at the southern tip of the chain, are some of the youngest. They are estimated to be around 600 years old (Miller, 1985). Figure 1 shows the chain and the relative location and time of eruption of the South Inyo Craters

A study performed by Mastin and Pollard in 1988 found that the craters were formed by a dike, an intrusion of magma coming up to the surface of the ground. They found this by analyzing the fault scarp and fissures around the area and comparing them to those made in a model of a dike coming towards the surface. A study published by Eichelberger, et al. in 1988 confirmed these results by drilling a hole and taking a core that undercut the southernmost crater (South Inyo Crater). They found an area in the core that they believe to be rock from around a dike. Figure 2 shows where the core was drilled and what they found in it.

A paper by Miller in 1985 described more details about the eruptions. These craters were formed by phreatic, or steam explosions. The dike came up and reached a layer of ground water, creating large amounts of steam, which led to an explosion. This happened for each of the three craters.

While there have been many publications detailing what made the craters explode and how it happened, there is a general lack of data on the specific order in which these three craters erupted. While it is agreed upon that there is a general trend of the craters towards the center forming earlier, these craters are too close together to be sure that that trend applies.

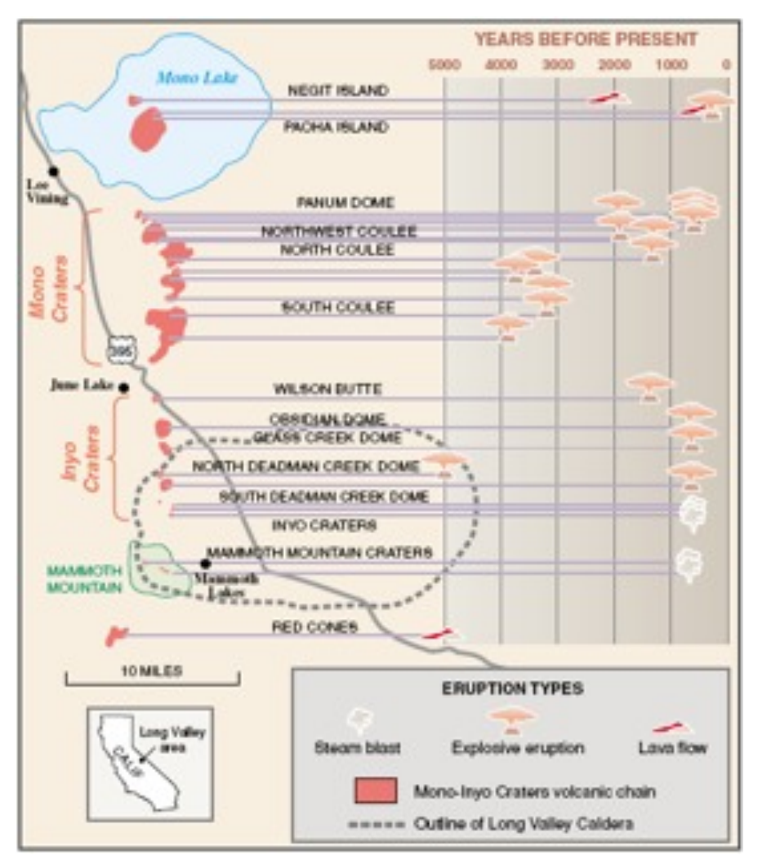


Figure 1: History of volcanic activity near Long Valley Caldera (Hill et. al. 1997).

II. Our Purpose

Because of this hole in the available information, our study focuses on finding the order in which the South Inyo Craters formed. We also hope to find information about how they formed and how they are important in terms of the geologic past and future of California. We hypothesize that the northernmost crater, Summit Crater, formed first, followed by the middle crater (North Inyo Crater) and lastly, the southernmost crater (South Inyo Crater) because evidence from ash layer composition and local geological context.

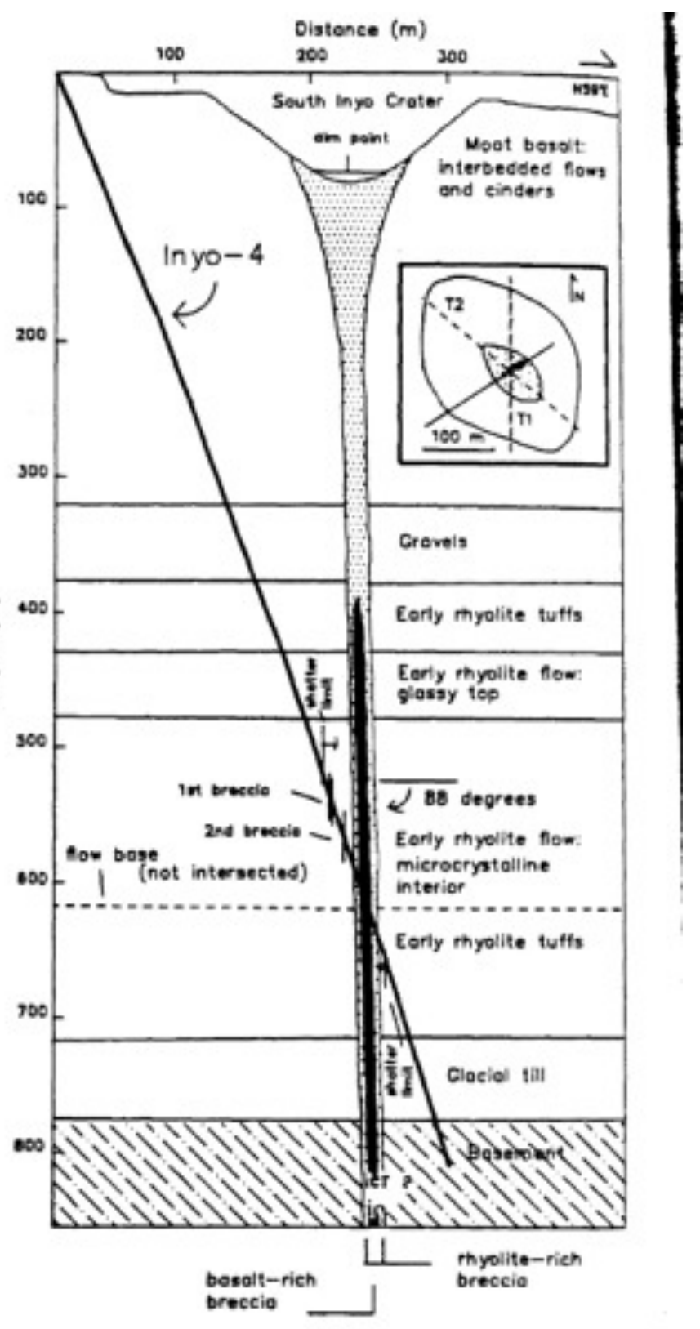


Figure 2: Subterranean petrographic survey revealing volcanic vent (Eichelberger et. al. 1988).

Methodology

I. GPS data gathering

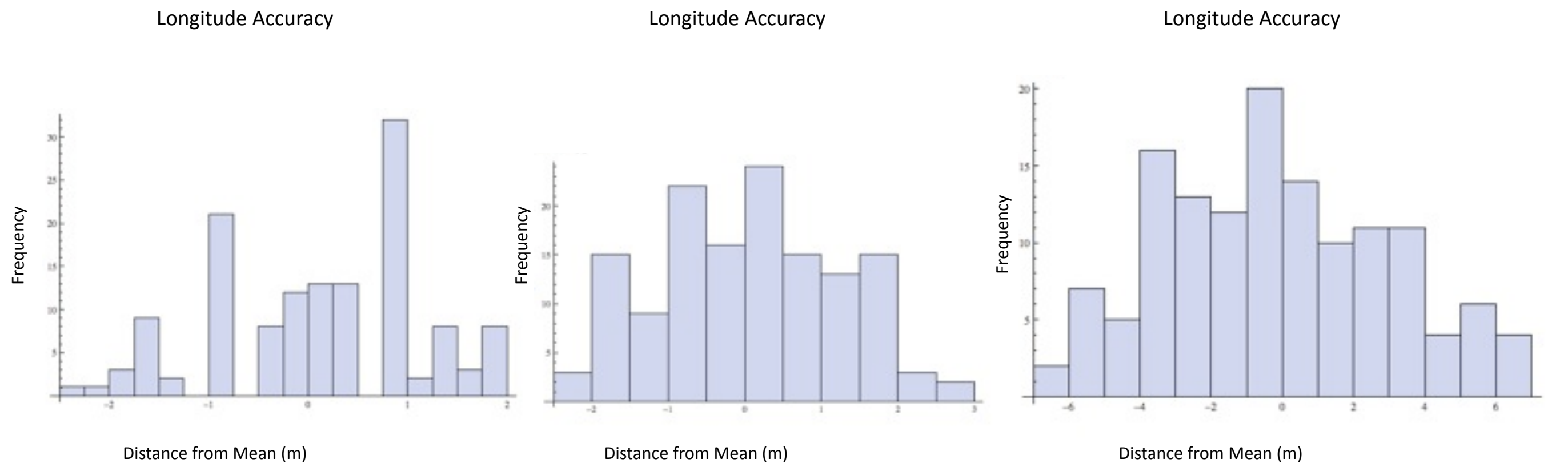
Using hand held Garmin GPSMAP 60Cs units, we collected data on the topography of the craters. We did this by walking around the rim, base, and walls of each crater and taking track points that recorded the latitude, longitude, and elevation of each point. These points allowed us to construct a digital elevation model (DEM) of the craters, using the WGS84 geoid. We also marked waypoints of locations of layers, rock types, and other important geologic features.

To assess the accuracy of the data gathered by the GPS units, we used 5 control points. Each of the points was marked on each GPS 4 times over the course of the day. Figure 3 shows histograms of the accuracy of the GPS units for latitude, longitude, and elevation. While the latitude and longitude readings were fairly consistent, the elevation readings were not as accurate as we had hoped. This became obvious as we began to construct our DEM. There were a lot of obvious outliers that we deleted for the purpose of consistency.

II. Rock Samples

We also collected rock samples from in and around the craters. The most important rock samples were from within the ash layers near the tops of each of the craters. For those and some of the others, we had thin samples taken so that we were able to compare their mineralogy under a microscope and determine whether the ash layers were the same in each of the craters. We performed a wide sweep of the area around the craters, gathering information about the rock types found in different places as a way of telling the location of each crater's ejecta location and making a geologic map of the area.

Figure 3: Histograms of variability in latitude, longitude and elevation measurements (from left to right). Latitude and longitude had standard deviations of approximately 2 m while elevation had standard deviation of approximately 5 m (Generated with Mathematica).



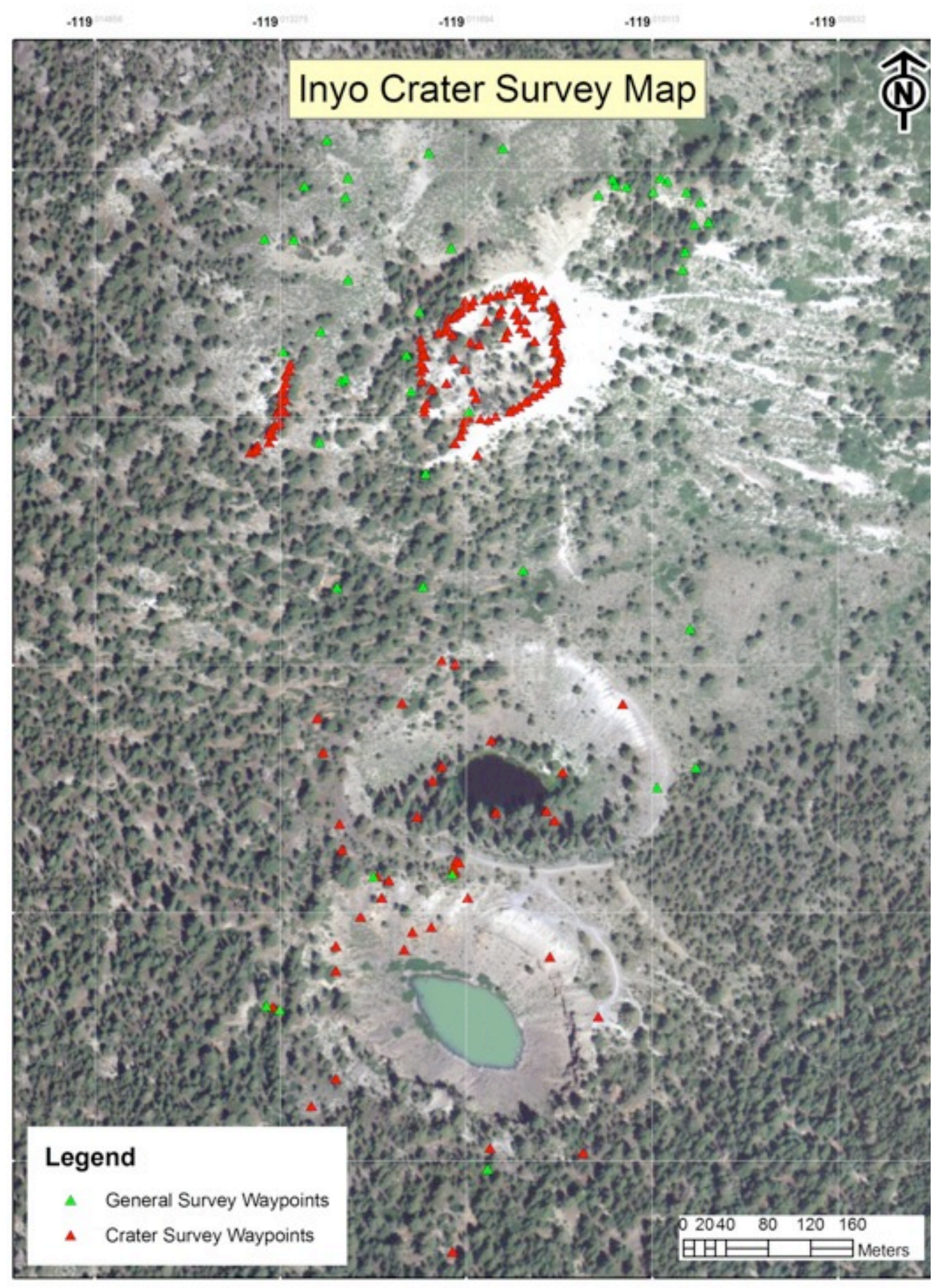


Figure 12: The Crater Survey Map shows the waypoints taken for both surveys carried out. The general survey was done on the area outside the craters, with the surveyors taking note of the types of rock, the types of minerals and the clast sizes in a 1 meter square area. The crater survey was done within the craters, taking note of similar notes, strike and dip measurements and also contacts between the layers.

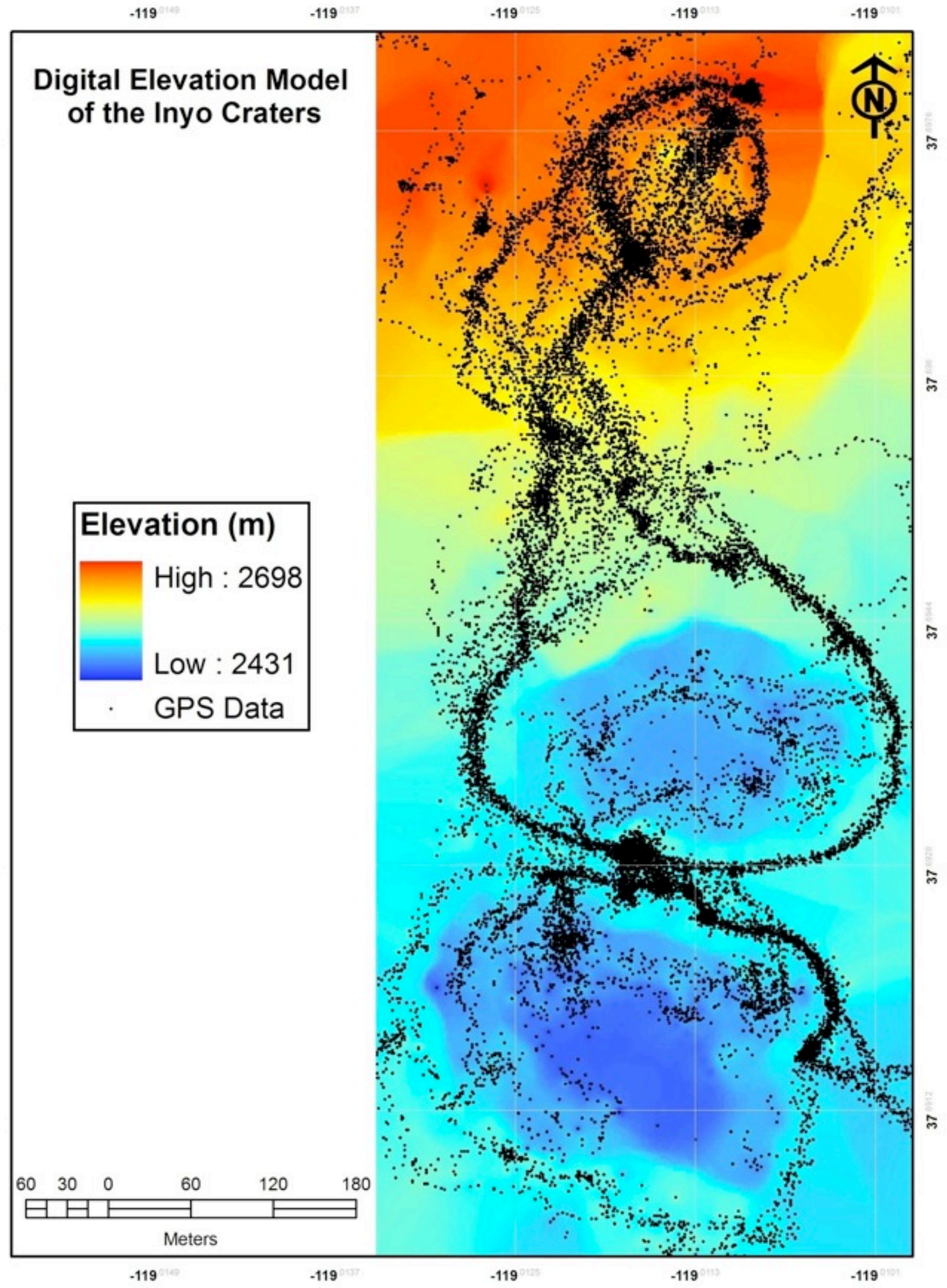


Figure 11: Digital elevation model for the Inyo Craters based on GPS data, displayed as a stretch map with GPS waypoints as black dots.

Summit Crater Geological Setting:

Measurements of the strike-dip in the craters were supposed to enable us to identify distinct geologic units in the craters. Three types of measurements were taken, strike-dip of bedding, jointing and banding (Strike-dip of banding is shown in Figure 13). The strike-dip measurements were supposed to help understand the crater's geological structure.

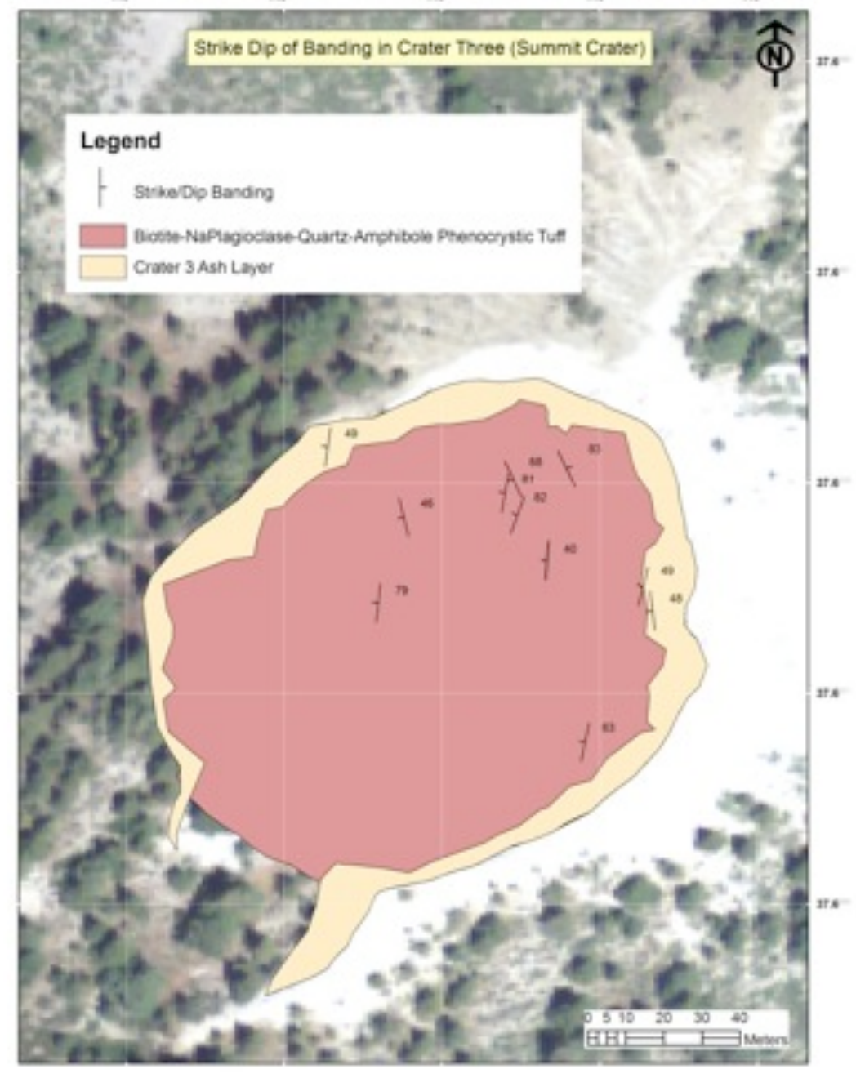


Figure 13: The Crater 3 area, derived from a satellite image, is marked in pink and the ash layer is shown in tan. The waypoints showing the strike and dip of banding is depicted to show how almost all the beds have a similar strike and dip showing that the eruption blew through pre-existing geological structures. The strike and dip measurements were also taken for banding and jointing, but these did not show any significant patterns that would have enabled us to identify any geologic units in the crater. The rotation direction of the symbol represents the strike, while the label shows the dip.

Extensional forces acting in the region are responsible for decompression melting of the asthenospheric mantle. Consequently, this has caused the melting and thinning of the overriding lithosphere (Bailey, 2004). Molten magma moves towards the surface due to the relative force of gravity. This in turn exerts a greater force on the denser surrounding material and may eventually reach a new buoyant equilibrium. As the magma moves closer to the surface, it begins to lose heat to the surrounding rocks and undergoes conformational change and fractional crystallization.

The Inyo Craters are in a seismically active zone (see figure 10). Since the start of the 1980s there has been an increase in the number of high magnitude earthquakes measured. In May, 1980, there were 4 magnitude 6 shocks which struck in quick succession. Earthquake activity within and adjacent to the caldera has remained low since mid-1999 averaging just five to ten earthquakes per day with magnitudes lower than 2 and occasional highs of 3. This constant low intensity seismic activity would progressively weaken the overlying lithosphere and make this lithospheric region more susceptible to magma extrusion. Because Long Valley caldera contains extensional faults, the formation of dykes is facilitated. The magma from the underlying magma plume heats the groundwater to a level where it turns into the steam and expands and in doing so causes a phreatic eruption.

The pattern of volcanic activity over the last 5,000 years suggests that the next eruption in the long-valley system will occur in close vicinity to the Mono-Inyo chain. Although Mono-Inyo craters is an integral part of the Long Valley Caldera system, it is geologically young having erupted only 600 years ago in quick succession, it is therefore not representative of the whole eruption sequence. However, it helps in explaining that this region continues to be an active seismic area and that unless there are changes in the seismological characteristics of the region, intrinsic volcanism will continue. The probability of a volcanic events and a significant timescale calculation is difficult to quantify without further data analysis and better understanding of factor inputs. The Inyo crater eruption will help in determining how the regions seismic properties have changed over time and how eruptions of this size could impact future human environments. It is likely that the explosive potential of future eruptions will be similar to these eruptions but will be small to moderate in size. Thus, while another phreatic eruption similar in nature and scale to the Inyo Craters' could happen, but would likely cause relatively little damage. Massive eruptions of the size accompanying the formation of Long Valley Caldera 760,000 years ago are extremely rare and scientists see no evidence to suggest that an eruption with such catastrophic implications are brewing.

Crater Volumes:

For the North and South Inyo Craters, track points and the DEM (Figure 11)were used to approximate the major and minor axes of three ellipses at different elevations: the crater rim, halfway down the crater wall, and at lake level. These axis measurements were then used to construct several frustums whose volumes could be easily calculated. In addition a correction was added to both volumes assuming maximal lake depth of 15 and 10 meters for crater 1 and 2, respectively (this is suggested in Maston 1991). Since crater 3 is on the face of Deer Mountain an alternate method was used. A paraboloid was fitted to crater walls and the volume of the paraboloid intersected with a plane (the preexisting slope of the mountain) was calculated.

Volume Estimates:
South Inyo Crater: $9.5 * 10^5$ m^3 ± $2.5 * 10^5$ m^3
North Inyo Crater: $6.2 * 10^5$ m^3 ± $1.8 * 10^5$ m^3
Summit Crater: $1.5 * 10^5$ m^3 ± $.45 * 10^5$ m^3

Accuracy: Due to variability in the elevation points used to construct the models, the actual values may be significantly different. Given the known variance of the elevation figures the maximal error falls in the range of +/- 30%, though if some of the variance in these measures is due to systematic error the relative magnitudes are somewhat more accurate than the absolute magnitudes.

These craters are therefore comparable in size—their volumes are within the same order of magnitude. An explosion forming a crater this size could only lead to a substantial (greater than 0.5 meter) ash fall in an area with a radius of less than two kilometers. There is thus little risk of large-scale damage due to another potential phreatic eruption in the Inyo Craters region.

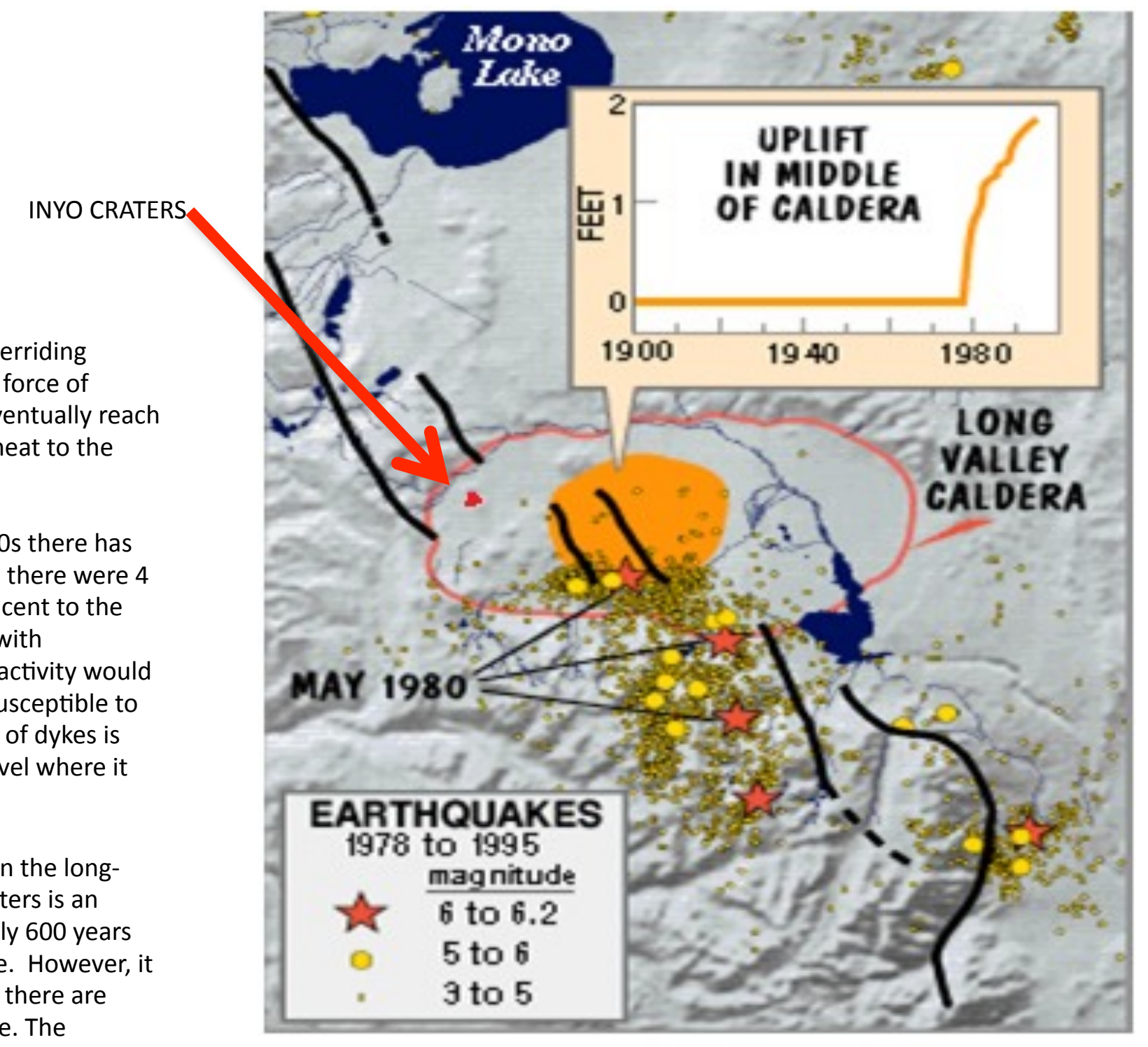


Figure 10 illustrates the spatial logistics of faults within the Long Valley caldera system and the density and magnitude of the earthquakes that have occurred during this 17 year period. It is evident from this scatter plot that a majority of seismic activity is between the range of 3 and 5. It also illustrates the rate and extent of central uplift. The Inyo Craters' location is marked by a red triangle.

Ash Layer Analysis

The northernmost crater will be called Summit Crater is it is at the top of Deer Mountain, the middle crater will be called North Inyo Crater and the southern crater will be called South Inyo Crater.

Each of the Inyo Crater explosions produced copious amounts of ash, which was deposited in the area to form distinct ash layers. Comparative compositional analyses of ash layers enable the reconstruction of the crater formation order.

Summit Crater's outcrop is primarily biotite-hornblende-plagioclase-quartz-feldspar tuff. The crater rim only exhibits one ash layer, containing clasts of the same composition tuff and basalt. The basalt, while not visible as outcrop, is presumably present underground and was brought to surface during the explosion. Figures 4 and 5 show similarities between the outcrop tuff in Summit Crater and the tuff found in the ash layer on Summit Crater's rim.

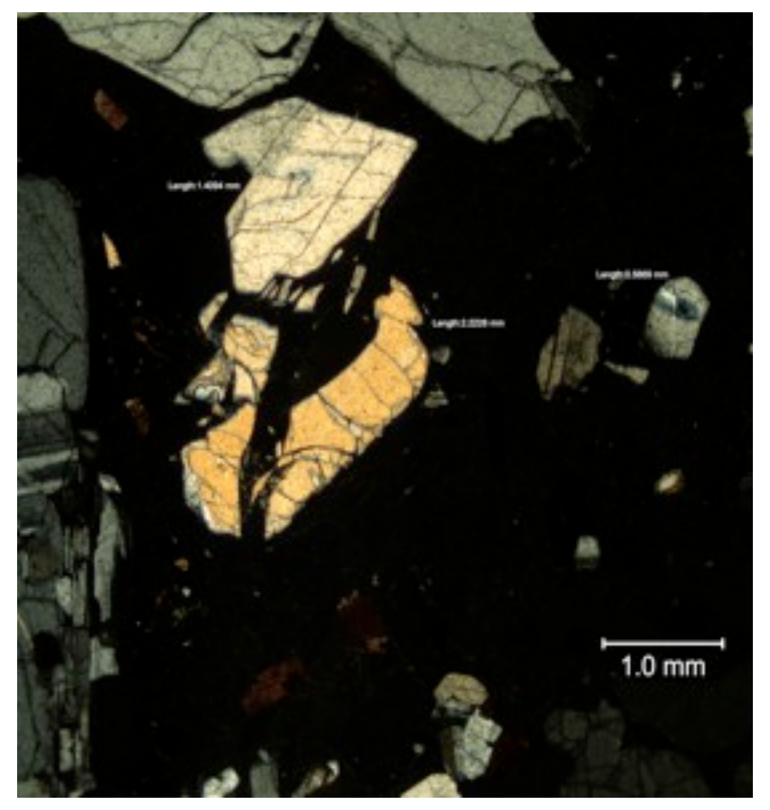
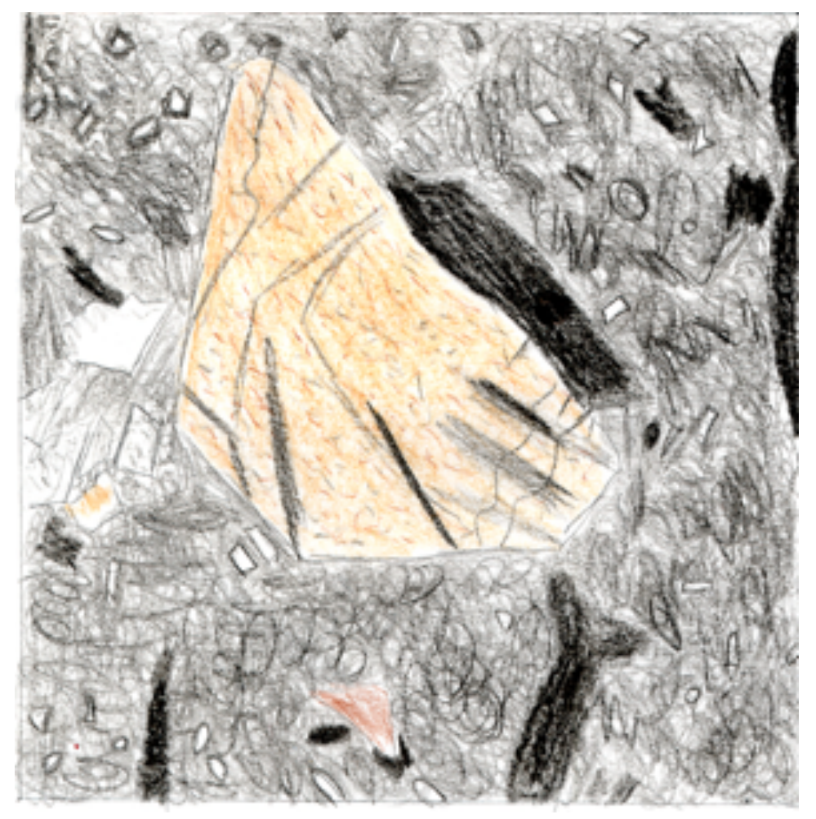


Figure 4: photo (above) and associated sketch (below) of a thin-section of outcrop tuff from Summit Crater. This tuff contains biotite, hornblende, Na-plagioclase, quartz, and feldspar.

Figure 5: Photo of a thin-section of ash layer tuff from Summit Crater. Like the outcrop tuff, this tuff also contains biotite, hornblende, Na-plagioclase, quartz, and feldspar.



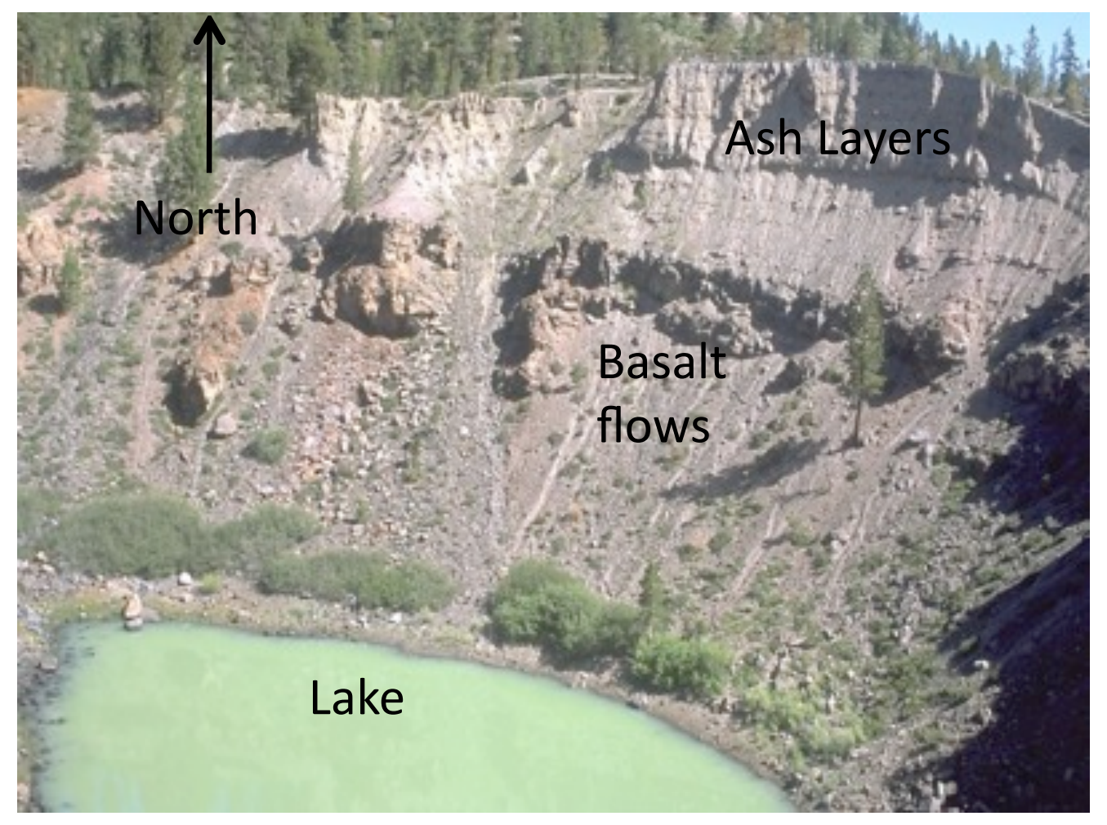
South Inyo Crater has many more ash layers (figure 7) than Summit Crater (figure 8), in addition to clearly exposed basalt layering (figure 6).

The lowest ash layer in South Inyo Crater appears similar to the ash layer from Summit Crater, containing tuff and basalt layers. The largest clasts are 40cm in diameter. A thin-section of tuff (figure 9) from the lower ash layer shows remarkable similarity to Summit Crater's tuff: both contain biotite, hornblende, plagioclase, feldspar and quartz. Crystal diameters in the two samples are slightly different:

	Summit Crater	S. Inyo Crater
Biotite	0.36 mm	1.11
Plagioclase	0.59	0.98

Diameters were not measured for other crystals. While the crystal sizes are not the same, the composition is very similar: the lower ash layer in South Inyo Crater contains tuff clasts from Summit Crater. Summit Crater must thus have erupted first.

Figure 6: Photo of South Inyo Crater (view to the North) showing locations of ash layers, basalt flows, and lake. Image by S.R. Brantley, August 1992



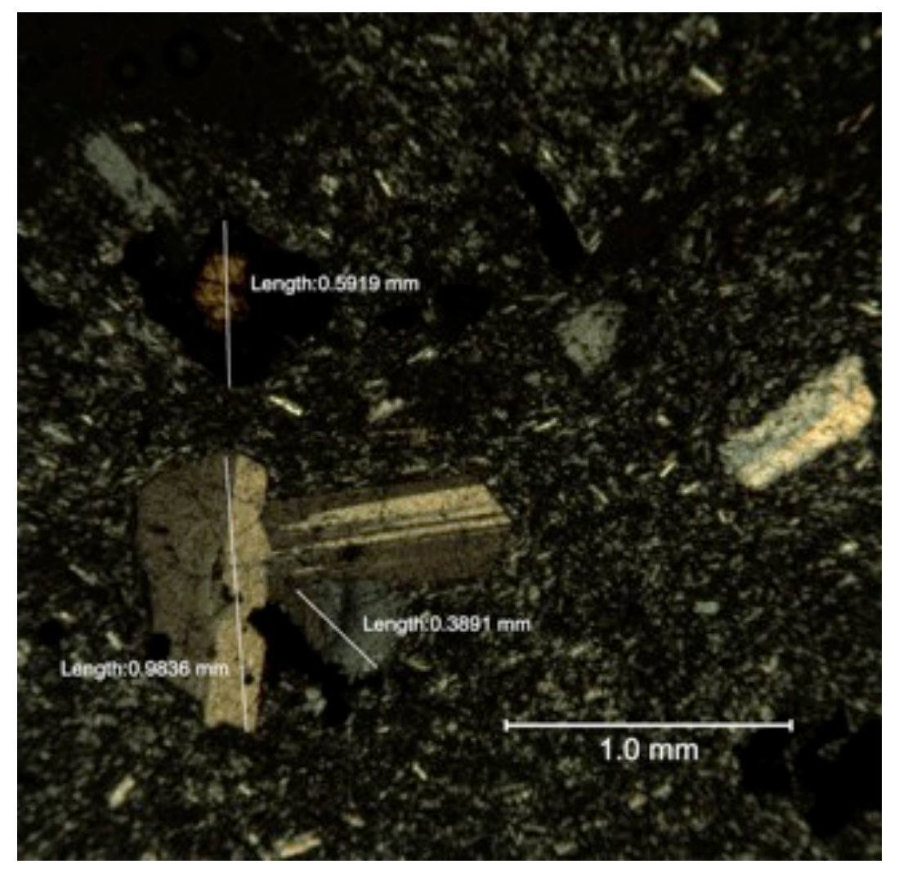


Figure 9: Photo of a thin-section of tuff found in the lowest ash layer of South Inyo Crater. This tuff also contains biotite, hornblende, plagioclase, quartz and feldspar. While the crystal sizes are not the same, the composition is very similar.

Figure 7: Schematic representation of ash layers in South Inyo Crater.

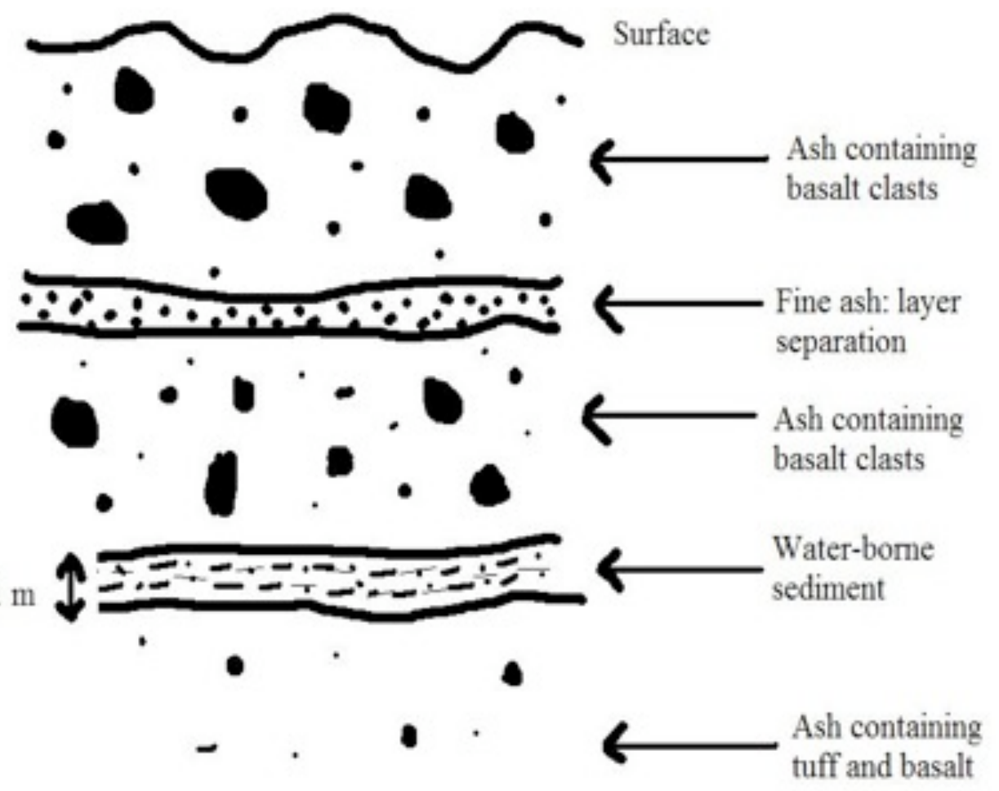


Figure 8: Photo of Summit Crater showing one ash layer border upon tuff outcrop.

The next layer in South Inyo Crater, about 1 meter thick, is not ash but coarse water-borne sediments. These are fairly evenly layered and contain pumice, tuff, and a few basalt clasts. The clasts are under 5cm in diameter. As the clasts are not very rounded, they did not travel far. Samples were not taken, so thin section analysis was not possible. Based on physical appearance, this layer could have been formed as a result of flooding after the Summit Crater explosion that washed away fine ash grains but deposited layers of larger clasts in the area.

Higher up in the South Inyo Crater is a 5-meter thick ash layer with a moderately coarse matrix containing many andesite clasts up to 80cm in diameter. The next – and topmost – layer of South Inyo Crater is similar, with large basalt clasts and a moderately coarse matrix. In between these ash layers is an unevenly delineated layer of lighter and finer clasts. They seem to belong to the middle layer, and show the separation between the two ash falls. During the basaltic ash fall, the finer grains took longer to fall and thus formed another small layer at the top of the regular ash layer.

No such separation exists on top of the top-most large layer of basaltic ash, as a layer of fine ash would easily be eroded. Thus, the presence of that fine ash layer indicates that the North and South Inyo Craters erupted in relatively quick succession. Finally, we can tell which crater erupted last by how each crater looks today. The inside of North Inyo Crater is smooth and looks filled in—this is due to being covered in debris from the South Inyo Crater eruption. It was thus not the last crater to erupt. The inside of South Inyo Crater, in contrast, is rocky and not filled with debris from any other ash fall: South Inyo Crater erupted last.

The order of eruption was thus first Summit Crater, then North Inyo Crater, and finally South Inyo Crater.

Analysis of North Inyo Crater is glaringly absent in this presentation. Indeed, while ash layers are very apparent on the northeast wall of North Inyo Crater (see figure 9), they do not contain clasts that can be used for thin-section and mineral analyses. However, the lowest ash layer in North Inyo Crater looked similar in composition to Summit Crater's ash layer. The middle layers in North Inyo Crater contain basaltic clasts and result from the North and South Inyo Crater eruptions. The top layer on the North Inyo Crater rim is composed of water-borne sedimentary deposits (different from those in South Inyo Crater) exhibiting substantial layering.

Figure 9: View to the northeast of the North Inyo Crater wall showing ash layers. The lower, lighter layer appears to be similar to Summit Crater's ash in composition. The darker layers contain basaltic ash.

Implications

The extent and magnitude of the phreatic eruptions at Inyo crater were limited in magnitude to a local area around Long Valley Caldera. The total volume of ejecta from these three eruptions was on the order of 10^6 m^3 while in comparison the eruption at Mt. St. Helens was 10^9 – 10^{10} m^3, several orders of magnitude larger. In addition extrapolation on data collected on basaltic ballistics indicates that basalt clasts of larger than .25m were confined to within 1 km of the craters. Together these indicate that there is negligible risk to persons or property outside of a 2-4 km radius from these eruptions. In comparison more serious volcanic eruptions can threaten much larger areas.

These eruptions were caused by magma from the Long Valley Caldera heating underground water to the point of explosion. This indicates that at the time of the explosion there was significant heating and magma collected at a depth where water collects. In terms of studying the activity of the Long Valley Caldera it is important to note its prior activity, so this information sheds light on the heating due to caldera magma at the time of the eruption.

Further Investigation

In order to get a better understanding of the eruptions we propose two more investigations. First it would be helpful in understanding the extent and magnitude of the individual eruptions if we had data on the size of the ash layers at points other than the crater walls themselves. We propose that holes could be dug at multiple areas around the craters to determine clast composition and ash layer depth corresponding to each individual eruption, data which could then be used to determine (and corroborate) total ejecta volume and eruption energy. In addition we propose that more extensive measurements of strike and dip be taken around the craters in order to determine the impact that the eruptions had on the pre-existing basalt flows in the area. Not only could this information be used to determine eruption energy but it could also be used to study the deformation of local basalts to eruption-like stresses.

Conclusions

We can conclude with a high level of certainty based on the data collected that the order of the eruptions is Summit, North Inyo, and then finally South Inyo. We are also lead to conclude through our data in addition to contextual research about Long Valley Caldera that the eruption was caused by magma associated with the caldera heating local groundwater reservoirs to the point of explosion. In addition, due to the distribution and extent of the debris fields we are lead to conclude that phreatic eruptions in general are relatively minor in extent, and that any damage to persons and property are contained within a 2-4 km radius of such an eruption.

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