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The Mt. Paektu Geoscientific Project

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Summary

Since 2011 UK, US and DPRK scientists have been collaborating to understand the eruption history and present state of Mount Paektu (also known as Changbaishan), a volcano that straddles the international border between DPRK and China. The scientific team are also investigating the hazards and risks that can be associated with future activity of the volcano, and the measures that can be taken to mitigate these risks. The volcano was responsible for one of the largest eruptions of the last few thousand years (the 946 AD 'Millennium Eruption') and recently experienced an episode of volcanic unrest characterised by increased seismicity and ground deformation, raising concern in the region around the potential for future eruptions. Our project involved a two–year installation of broadband seismometers near the volcano, collection of more than 100 geological samples for analysis in European and American laboratories, and field investigation of rock outcrops on flanks of the volcano. Highlights of the project include seismically imaging melt distribution, show a region of partial melt below 7 km depth and extending ~20km from the volcano summit, estimating the volatile budget of the Millennium Eruption, showing evidence that the Sulphur release may have been comparable to Tambora, constraints on the trigger mechanism for the Millennium Eruption, showing a basaltic trachyandesite remobilizing two existing magma chambers and finally the first absolute date for the Millennium Eruption to late 946 CE. Despite these successes, significant questions remain about the origins, history and hazards and associated risks at Mt. Paektu. Future research projects are being designed to address these.

Keywords: Mt. Paektu Volcano, Seismology, Petrology, Geochemistry, Geochronology

1 Introduction

Starting in 2011 UK, US and DPRK scientists have been collaborating to understand the eruption history and present state of Mt. Paektu, a volcano that straddles the international border between DPRK and China. The scientific team is also investigating the hazards and risks that can be associated with future activity of the volcano, and the measures that can be taken to mitigate these risks. The volcano is best known for the 946 CE, VEI 7 eruption, which resulted in significant ash fallout as far as Japan and the Kuril Islands and ash found in Greenland ice cores [14] (Fig. 1. a).

This catastrophic event, combined with a recent episode of unrest (2002–2005) signaled by increased seismicity, ground deformation and geochemical anomalies [15] has focused significant attention on the volcano. As a result, monitoring efforts have been upgraded on both sides of the international border. In 2011, members of our consortium, the Mt. Paektu Geoscientific Group (MPGG) were invited to DPRK to develop projects on the volcano. Our project, primarily funded by the American Association for the Advancement of Science, The Richard Lounsbery Foundation, the Natural Environmental Research Council and the Environmental Education Media Project, involved a two–year installation of broadband seismometers near the volcano, collection of more than 100 geological samples for analysis in European and American laboratories, and field investigation of rock outcrops on flanks of the volcano. Since this time we have also cultivated collaborations with scientists from the China Earthquake Administration (CEA). As a result, we have been able to work with both DPRK and Chinese scientists to begin to address some of the fundamental questions surrounding Mt. Paektu. In this presentation we will describe the aims and background of the project and summarise the main highlights. Finally, we will make some proposals for future research at Mt. Paektu.

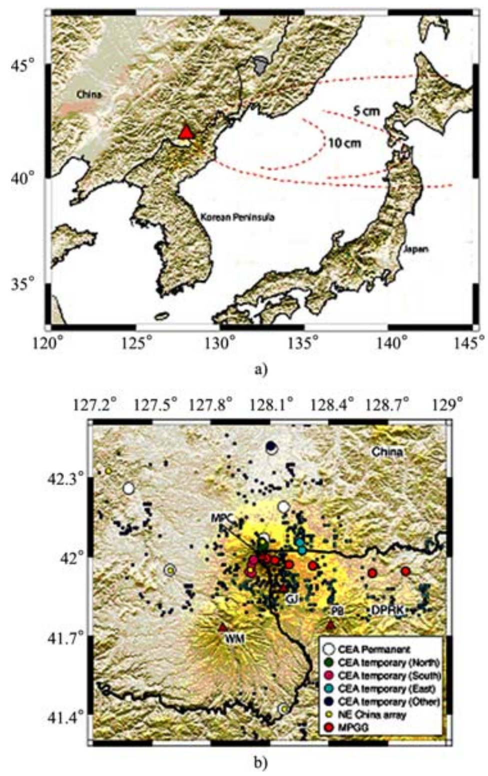

Figure 1. a) The location of Mt. Paektu. Dashed red lines show the fallout from the 946 CE 'Mileniumm Eruption' (after ref. 1). b) Seismic stations used in the MPGG study. Red circles show stations deployed by MPGG, other symbols show stations deployed by the China Earthquake Administration. Light blue and dark blue circles show the receiver function coverage of Kyong–Song et al., 2016 and Hammond et al., in review respectively.

2. The Mt. Paektu Geoscientific Project

At the 2011 Samjiyon workshop the following aims were agreed for DPRK–UK–US collaborative research:

Determine the underlying structure through geophysical imaging

Understand the pre–946 CE eruptive conditions through petrology

Understand the style of the 946 CE eruption from volcano–stratigraphy

Initiate discussion of the risks posed by a future eruption of Mt. Paektu

This involved 3 field campaigns in the summers of 2013–2015. During these trips, 6 broadband seismometers were deployed in an approximately linear profile heading east from the summit of Mt. Paektu. Additionally, over 100 geological samples were collected, mainly focusing on the 946 CE eruption, but also collected from other older and supposedly more recent eruptions.

3 Seismology

Continuous seismic data was recorded at the 6 stations recording with a sample rate of 50Hz. The main aim for the geophysical imaging was to use the receiver function technique. This has been shown to be a powerful method to image large scale changes in crustal structure and has previously been used to identify the presence of partial melt in volcanic areas [4].

3.1 Receiver Functions

The receiver function method works by isolating any P–wave to S–wave conversions that happen directly beneath a seismic station. If seismic data is recorded on 3 orthogonal components, then teleseismic signal recorded on the vertical component contains mostly P–wave signal, whereas the horizontal components contain a combination of P– and S–wave signal. Therefore, through deconvolving the vertical component signal from the horizontal, only the P–wave to S–wave conversions should remain. The results of these studies have been published [5, 12], but the main results are discussed here.

Receiver functions typically contain information on major discontinuities beneath a seismic station. In most cases, the clearest signal comes from the crust–mantle transition (Moho). It is possible to identify these signals together with energy that reverberates in the crust in the receiver function data. If so, the arrival times of these data are sensitive to the crustal thickness and ratio of P–wave to S–wave velocities (V_P/V_S). This is the basis for the H–k stacking technique (see [19] for details). Results of H–k stacking show that the crust far from Mt. Paektu is typical of continental crust with a thickness of ~35 km and a V_P/V_S of 1.75~1.8. However, for stations close to Mt. Paektu, the crust thickens to ~40km and the V_P/V_S increases to >1.9.

We determine more detailed view of the crust through common conversion point migrations. We follow the methods outlined in [4]. These models show the crust thickening beneath Mt. Paektu and also highlight significant internal crustal structure (Fig. 2). Most prominent is a strong negative peak, typically associated with a velocity decrease with depth at 5~10km. However, it has been shown that reverberations in shallow structure can cause similar features in receiver function data. To test this hypothesis we perform grid search inversions [7] to test if a velocity reduction is necessary.

It is evident that the 4 stations close to Mt. Paektu require a significant velocity reduction at ~7km depth.

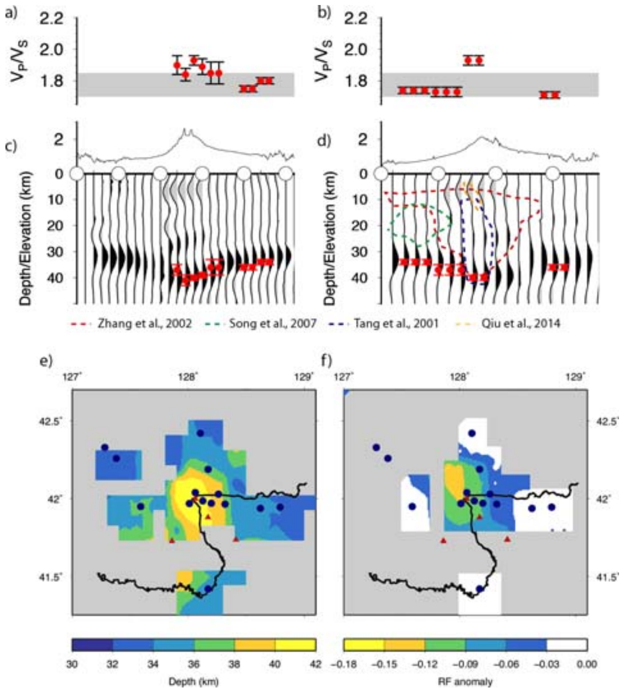

Figure 2: a, b) V_P/V_S determined from H–k stacking, c, d) Common conversion point migrations for East–West and North–South profiles corrected for shallow structure. Coloured dashed lines show previous estimates for low velocity and high conductivity regions. See Figure 1 for locations of profiles. e) Map of Moho depth derived from the common conversion point migrations. f) Map of the strength of the low velocity anomaly at ~7km depth. After [5].

With this information we can correct the receiver function migrations for shallow structure better highlighting the low velocity region and allowing us to map out the spatial extent of the low velocity zone (Fig. 2). The location of this feature directly beneath Mt. Paektu and extending laterally by ~20km is co–incident with the high V_P/V_S suggests that partial melt is the cause of this feature. This co–incides with other estimates for a shallow magma reservoir beneath the volcano [11, 15, 18] and suggests that the recent volcanic unrest may have recharged this shallow system.

4. Geochemistry

Following field seasons in 2013 and 2014, a total of 94 rock samples have been analyzed. In addition, high pressure, high temperature experiments have been carried out on the Millennium comendite and melt inclusion studies have also been undertaken on the Millennium eruption rocks [6]. The volatile contents of melt inclusions were analyzed, and compared with mineralogical evidence for volatile evolution in the melt, including the presence of a sulphide phase. Overall, the melt inclusion studies suggested that the sulphur budget for the Millennium eruption may be higher than previously assumed, and that the lack of any significant climate signal in ice core records likely reflects the high latitude of the volcano.

S canning electron microscopy and mineral compositions, as well as glass compositions in the Millennium eruption samples, suggest that the eruption was likely triggered by magma mixing involving a basaltic trachyandesite that remobilized two existing bodies of magma – the comenditic white pumice and the trachytic black pumice, in that order. There is very little textural evidence of mixing between the comendite and the trachyte, but there is mixing between both of these endmembers with the basaltic trachyandesite.

The comendite in particular is relatively low temperature, based on thermodynamic modelling and experimental results. Further work is needed to model crystals from other eruptive units.

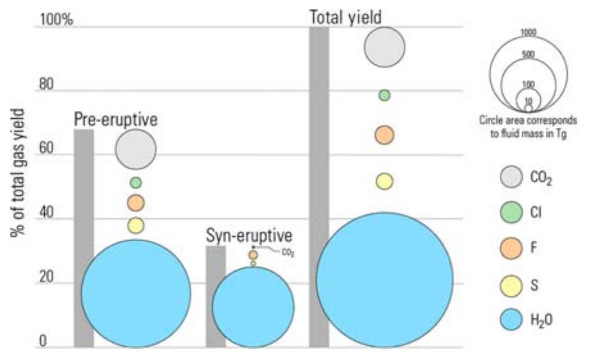

Figure 3: Figure showing the proportional contribution and composition of pre– and syn–eruptive fluid. Also shown is the total gas yield. After [6].

Analyses of older samples including several older trachytes, older rhyolites and old basalts suggest at least two large magnitude eruptions producing substantial ignimbrites (at least one comendite and one trachyte), and numerous smaller eruptions.

5. Geochronology

Previous estimates for the date of the Millennium Eruption ranged across the 10th Century(Fig. 4).

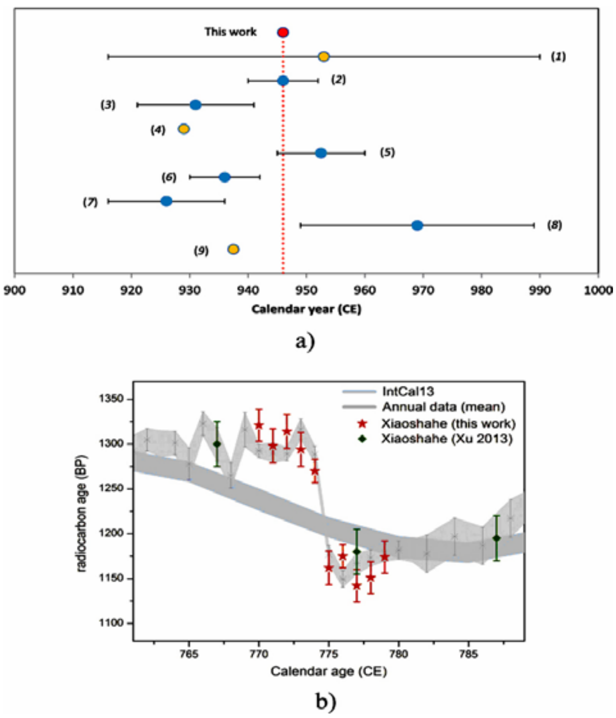

Figure 4: a) Range of dates proposed for the Millennium Eruption. Numbers refer to references (see Oppenheimer et al., 2017 for references). High resolution radiocarbon ages (red and green symbols) and associated 1σ uncertainties. Also shown are radiocarbon measurements from Japan (grey dots) and Europe (grey trace). The IntCal13 14C calibration curve is also shown. After Oppenheimer et al., 2017.

Despite this uncertainty, ash from the Millennium Eruption (known as the Baegdusan–Tomakomai ash (B–Tm layer) in stratigraphy) has often been used as a key stratigraphic marker in paleoenvironment and archeological studies [2]. Recent studies have used large trees (Pinus and Larix) that were destroyed by pyroclastic density currents during the eruption [16, 17] to perform wiggle–matching to date the eruption. However, while these represented the best dates available, they still only constrain the date of the eruption to within a few years. The tree used in one of these studies (Xu et al., 2013) was 264 years old when killed by the eruption, meaning it was alive in the year 775 CE. This is important as that year has been identified as the year of an ephemeral burst of cosmogenic radiation seen in 14C tree ring measurements worldwide (Miyake et al., 2012, Buntgen et al., 2014, Guttler et al., 2015) and ice cores in Antartica and Greenland [13]. In our study [9], we perform a high resolution measurements of ^{14}C to identify this tree ring allowing us to determine the exact year the tree was killed by the eruption (946 CE). Further, the presence of latewood suggests the tree was either killed during autumn or winter of 946 CE. This new constraint allows us to investigate the historical records and two records exist that may provide further insights on the date of the eruption. A loud disturbance: “That year the sky rumbled and cried out.” Is recorded in the history of the Koryo dynasty and on 3rd November 946 CE it is recorded that “white ash fell gently like snow” in Nara (Japan), but ambiguity in these descriptions means we should be cautious in ascribing a day to the eruption. However, the now well constrained date allows the B–Tm stratigraphic marker to be used for absolute dating archeological sites and other eruptions with more confidence (e.g., [10]).

Despite the size of the eruption and these new constraints on its timing, there is little evidence for significant cooling effect seen in other eruptions (e.g., Tambora), suggesting that, if significant Sulphur is released [6], some mechanism such as its high latitude must have restricted its effects.

6. Future Work

Future work will involve establishing an agreed stratigraphy that can be used for hazard assessment via probabilistic modelling. It will also include simple flow models for eruption scenarios based on the past eruptions, and some work to develop emergency plans and an alert level system to manage the volcano.

Additional petrological work will be done on the existing samples to establish their basic petrology, particularly the mineral chemistry. This will allow modelling of magma chamber conditions using available thermodynamic models, geobarometers and geothermometers.

Future geophysical work will use new seismic deployments in both DPRK and China to understand melt distribution beneath other nearby volcanoes. The addition of other geophysical data (e. g., gravity, magnetotelluric, magnetic) would further constrain melt distribution. New larger seismic arrays will also help address questions on the origin of Mt. Paektu.

7. Conclusions

The Mt. Paektu geoscientific project running since 2011 has had a number of successes:

Constraining melt distribution through seismic imaging [5, 12].

Determining the Millennium Eruption triggers through petrology.

Understanding volatile budgets through geochemistry [6].

Absolute dating of the Millennium Eruption to 946 CE [9].

However, a number of questions remain outstanding such as; what is the origin of the volcanism at Mt. Paektu? What is the long–term history of volcanism in northern DPRK and north–east China? What are the hazards and associated risks at Mt. Paektu. More research is required to address these questions.

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