A thermomechanical perspective on caldera formation and classification

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Decades of research have led to a mature understanding of caldera formation and evolution. In particular a temporal model for caldera formation (Smith and Bailey, 1968) is now well understood and morphological classifications based on geological studies (e.g. Lipman, 1997; Cole et al, 2005), recently informed by analogue models (Acocella, 2007), capture the final surface manifestations and styles of collapse and inferred relationships to chamber depth, size, and shapes (Lipman, 2000; Roche et al., 2000; Kennedy, 2000). However, our understanding of the processes that lead to these morphologies and the temporal evolution remain murky. In particular, what initiation and triggers catastrophic caldera collapse is unclear. The general two stage model of collapse (Stages 2 and 3 of Smith and Bailey, 1968) is the paradigm that prevails (Druitt and Sparks, 1984; Kennedy and Stix, 2003). In this model an initial eruption is triggered by overpressure in the magma chamber. Evacuation of magma and bleeding off the overpressure leads to an underpressured condition in the magma reservoir that triggers caldera collapse and pyroclastic flow generation. However, it has been increasingly recognized that many of the largest calderas do not conform to this two-stage model and involve catastrophic caldera collapse at the inception of eruption (Christiansen, 2005; de Silva et al., 2006). Moreover, many of these large calderas exhibit a significant structural resurgence that smaller systems do not. Large caldera collapses result in collapse of the entire upper crust above the magma system, smaller calderas form within the edifice. The details of the physical volcanology of the eruptions and the resulting ignimbrites are quite different.

These differences between large and small calderas can be understood from a thermomechancal perspective. Generation of viable large magma bodies requires elevated thermal fluxes and thermally mature crust (de Silva and Gosnold, 2007; Annen, 2009) that plays a fundamental role in the rheology of magma/host rock interface (Jellinek and DePaolo, 2003) and ultimately controls magma reservoir growth, pressure evolution, surface uplift, faulting, and caldera size (Gregg et al, 2012, 2013). In particular thermomechanical considerations suggest that in large systems the catastrophic caldera eruptions are "externally" triggered by mechanical failure of the roof. Smaller systems are "internally" triggered by overpressure within the magma reservoir. These different modes of triggering largely control the final form of the calderas and the character of the eruption and associated pyroclastic deposits. We suggest that catastrophic calderas can be fundamentally divided into two size divisions with an approximate boundary at 10km diameter, 100 km^3 and VEI=7. Ultimately this is a thermal or thermomechanical divide.

Fail or not to fail? Reservoir mechanics and ground deformation before large magnitude eruptions of intermediate magmas

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The current knowledge base on ground deformation prior to the eruption of intermediate magma is skewed towards small magnitude eruptions. The long-term (order of years) pre-eruptive ground deformation of a future large magnitude intermediate eruption similar to the caldera-forming Great Tambora eruption in 1815 is thus poorly understood.

Here, we explore a potential long-term pre-eruptive geodetic signature of a growing magma reservoir of intermediate composition using numerical mechanical modelling.

We start by exploiting cyclic ground deformation data from the currently active Soufrière Hills volcano to constrain the pre-eruptive subsurface stress history of a comparably small magmatic system of intermediate composition. We first define a reservoir failure criterion based on rock tensile strength under the simple assumption of elastic mechanical behaviour of surrounding rocks. Given observed pre-eruptive deformation amplitudes and petrologically deduced storage conditions, the results indicate that invoking mechanical elasticity is problematic to explain cyclic eruptive behaviour at SHV over the past decade. Time-dependent stress relaxation must play a first order role.

Up-scaling to match magmatic conditions prior to the Great Tambora eruption demonstrates a first order influence of edifice load, topography, and mechanical heterogeneity of encasing rocks on the stress distribution and the resultant deformation field upon reservoir growth. Again time-dependent stress relaxation is found to control growth of an intermediate magma reservoir of substantial size and thereby inhibiting pre-mature failure upon recharge.

The modeling also shows that a dynamic failure criterion is more plausible compared to a static criterion based on rock tensile strength to characterize reservoir failure at lithostatic pressures of between 100 and 220 MPa, i.e., within a pressure window constrained petrologically for many recently erupted intermediate magmas. Combining the numerical results with published thermal and petrological constraints on reservoir evolution, we deduce a limiting permissible volumetric strain rate upon reservoir recharge of 10^8 s^{-1}. Growth of a large body of eruptible magma of intermediate composition may be favoured at strain rates $<10^8$ s^{-1}, whereas pre-mature reservoir failure may occur at strain rates $>10^8$ s^{-1}. The associated long-term pre-eruptive ground uplift of the pre-1815 Tambora volcano by the incremental growth of a relatively short-lived (compared to silicic) intermediate magma reservoir is predicted at well below 1 cm/year. The results may be useful for assessing the long-term pre-eruptive signs of future large magnitude eruptions

Thermal-mechanical models of magma chamber pressurization: Implications for chamber growth and caldera formation

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Rapid magma chamber overpressurization due to the influx of new material or the exsolution of volatiles is often cited as a triggering mechanism for the eruption of a shallow magma chamber. Specifically, the increase in chamber overpressure may drive the tensile stress along the chamber boundary above the tensile strength of the surrounding wall rock and trigger a dike or sill intrusion and/or eruption. A major limitation to previous numerical and analytical models of magma chamber rupture is that overpressure is assumed constant and applied as a fixed boundary condition. This fixed boundary condition does not allow magma chamber expansion to dissipate overpressure. Understanding how overpressures build is critical for determining eruption triggers. In this study, we utilize thermomechanical models to investigate how magma chambers overpressurize as the result of either the influx of new melt or volatile exsolution. By incorporating an adaptive reservoir boundary condition we are able to track how overpressure dissipates as the magma chamber expands to accommodate internal volume changes. We find that the size of the reservoir greatly impacts the resultant magma chamber overpressure. In particular, overpressure estimates for small to moderate sized reservoirs (1-10 km^3) are up to 70% lower than previous predictions. Furthermore, our models indicate that systems >100 km^3 do not generate large overpressures, because magma volume changes are accommodated by deformation of the viscoelastic host rock. We apply our models to Santorini Volcano in Greece where recent seismic activity and ground deformation observations suggest the potential for a large caldera forming eruption. A viscoelastic model with a fixed overpressure boundary condition predicts a much lower magma flux than calculated using a Mogi source. This suggests that the increase in volume flux is much more modest than has been indicated in previous investigations. Conversely, the incorporation of an adaptive boundary condition reproduces Mogi estimations of a high magma flux and suggests that the magma reservoir present at Santorini may be quite large. Model results further indicate that, if the magma chamber is >100 km^3, overpressures generated due to the high magma flux may be below the tensile strength of the host rock, thus requiring an additional triggering mechanism for eruption.

Caldera development during explosive eruptions

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An interesting question is the likelihood that an explosive eruption results in caldera formation. Large eruptions emitting 10^2-10^3 km^3 of magma invariably form substantial surface subsidence structures, but smaller eruptions emitting 5-10 km^3 may not. These smaller events show variable behaviour, which is generally unpredictable, ranging from well-developed caldera structures (e.g., Pinatubo) to no calderas at all (e.g., Huaynaputina). For such events, is it possible to establish, during or even prior to the eruption, the probability that a caldera will form? Such an assessment is important, as the style of the eruption depends in part upon whether a caldera forms. One clear control is depth to the top of the magma reservoir; as depth increases, surface subsidence is reduced due to the crustal column between the surface and the top of the reservoir. A second important consideration is the amount of eruptable magma in the reservoir. An eruption that efficiently drains such eruptable magma from the reservoir may suddenly cease, putting a halt to caldera development. The caldera volume is commonly smaller than the volume of erupted magma, and this is a reflection of the mismatch between efficient magma extraction and surface caldera response. There is general recognition that many volcanic systems are underlain by a series of magma reservoirs stacked vertically in the crust and connected at times. There may thus be a balance between the relative roles of a shallow reservoir at 4-10 km depth and a second reservoir at deeper crustal levels which together may influence surface conditions including caldera subsidence. If the shallow chamber is small or largely crystallized, then the deeper reservoir may play a greater role in controlling the nature and size of the eruption. If the shallow chamber is large or largely liquid, then its influence will dominate. A fundamentally important aspect of this stacked magmatic system is that the shallow and deeper reservoirs are connected, allowing magma to be transferred from the deep to the shallow reservoir. The connection may be established, before, during, and/or after the eruption. Large explosive eruptions commonly appear to have this connection established prior to the eruption, allowing deep magma to (a) interact and mobilize shallow magma and (b) trigger the eruption. Magma erupted from the shallow reservoir unloads the system, providing a feedback for inflow of magma from below, perhaps at accelerating rates at later stages of the eruption and immediately afterward. Forecasting caldera formation during an eruption may be possible. Since surface caldera development is commonly a late-stage eruptive phenomenon which is preceded by subsurface faulting and subsidence, geophysical approaches (e.g., seismology, geodesy, gravity) may be used to identify subsurface processes such as faulting and development of voidspace which migrate upward in time.

Analogue caldera collapse models characterized with radiography and computerized X-ray micro-tomography

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Analogue models are widely used to investigate volcano-tectonic processes, their structural geometries, kinematics and dynamics. Past models explored caldera collapse structures mainly via 2D model cross–sections. For interpreting field and monitoring data, however, it is essential to understand the kinematics and geometry of caldera collapse structures in 3D. We applied high resolution radiography and computerized X–ray micro–tomography (μCT) to image the deformation during analogue fluid withdrawal in small-scale caldera collapse models. High resolution interval radiograph sequences provide an unprecedented ′2.5D′ documentation of the surface and internal model geometries, as well as of the kinematics of a collapsing column into an emptying fluid body. Subsidence was controlled by ring faults and associated with dilatation of the analogue granular material within the collapsing column. The subsidence rate within the collapse column showed three main phases: 1) Upward migration of a high velocity zone associated with ring fault propagation, 2) Rapid subsidence with the highest subsidence rates within the uppermost subsiding volume, 3) Relatively slower subsidence rates over the whole column but with intermittent accelerations of discrete sections of the column. By using radiograph sequences, it is possible to obtain a continuous observation of fault propagation, down sag mechanisms and the subsequent development of collapse structures in a non-destructive manner. μCT scans of the post collapse model enable a full 3D reconstruction of the model and its internal structure. The models highlight the possibilities and limitations of μCT scanning to qualitatively image and quantitatively analyse deformation of analogue volcano–tectonic experiments. Despite some practical model limitations, the radiograph and μCT method is hence a step towards a quantitative documentation of analogue models that would render experimental data more immediately comparable to recent monitoring data. The models also carry the potential for a better understanding of the kinematics of caldera collapse amongst a variety of volcano–tectonic processes.

Coupled long- and short-term eruption precursors during caldera unrest

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Short-term forecasts rely on accelerations in precursory signals. Although the strategy has proved suitable at stratovolcanoes reawakening after centuries of repose, it has been less successful at large calderas, where unrest may continue for decades or more. Here we argue that patterns of short- and long-term unrest are strongly coupled at large calderas, so that reliable interpretations of short-term precursors require knowledge of preceding episodes of long-term unrest.

During unrest, potential precursors may show significant variations in their rates of change with time. More than one episode of increased rate may decay without eruption. Associated warnings of eruption can be viewed as false alarms by local communities, who may then be reluctant to respond during future alarms. A classic example is the 21 years of unrest before the 1994 eruption in Papua New Guinea. An uplift of c. 2.3 m was recorded across the north of the caldera. Nearly 40% of the uplift occurred in 1982-84, accompanied by elevated rates of volcano-tectonic (VT) seismicity. The uplift rate of c. 0.45 m/yr was a magnitude larger than typical values over the 21-year interval. The 1982-84 crisis ended without an eruption. When an eruption finally occurred in 1994, it began without a significant increase in uplift rate and with an elevated VT event rate only 24 hours beforehand. An apparent contradiction thus exists in which significant precursory changes occurred without eruption, whereas an eruption occurred without significant precursory changes.

The contradiction is resolved by comparing changes of precursors with each other, rather than with time. The results yield an exponential dependence of VT event number on uplift. The trend is consistent with a single precursory sequence, during which damage accumulates in the crust until a new pathway is formed to feed an eruption. The amount of damage increases as the crust is stretched under a combination of (1) a build-up of pressure in an underlying magma reservoir and (2) movement of magma through the crust. Thus, the 1973-94 sequence can be related to a long-term increase in magma pressure, coupled with the shallow intrusion of a small batch of magma during 1982-84. At the time of intrusion, the amount of accumulated damage was too small to propagate a new pathway to the surface and so the event culminated in a non-eruptive crisis. By 1994, however, the amount of damage accumulated since the early 1970s had reached a critical amount, such that another episode of magma movement triggered the opening of a new pathway and led to an eruption after a very short interval of elevated precursory signals.

Growth and rupture of the Minoan magma body, Santorini

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The eruption of large silicic magma chambers following prolonged periods of crustal intrusion raises the question of what ultimately initiates venting. It is commonly invoked that the chamber pressure and or crustal stress state increases until some threshold is exceeded. I present evidence bearing on the trigger of the late 17th century BC Minoan eruption of Santorini, which discharged 30-60 km3 of magma. Three juvenile components were erupted: rhyodacitic pumices (>99 %), cauliform andesitic enclaves and crystal-rich andesitic pumices. The rhyodacite has 70-71 wt% of silica with about 10 wt% of phenocrysts set in rhyolitic glass. The enclaves have cauliform surfaces, variably ellipsoidal to tabular shapes, silica contents of 52-61 wt% and consist of 20-40 wt% of phenocrysts and fragments of disrupted gabbro set in silicic andesitic groundmass. Some have skins of adhering pumice showing that they are quenched mafic enclaves released from the rhyodacitic host on eruption. The tabular enclaves may be detached selvages from the margins of a composite dyke. The crystal-rich pumices have silica contents of 52-64 wt%, 40-60 wt% of crystals, and rhyolitic glass. They grade texturally into glass-bearing and holocrystalline nodules of hornblende diorite, and are interpreted as the contents of a variably crystallized intrusion - melt-dominated interior, crystal-dominated margins and holocrystalline carapace - that were disrupted, mixed together and discharged during the eruption. The enclaves, crystal-rich pumices and dioritic nodules formed from a batch of Ba-rich, Zr-poor andesite that is unique in Santorini products of the last 550 ky. Their high Ba/Zr ratios shows that the andesites are not related in any simple way to the rhyodacite. The crystal-rich pumice is the dominant magmatic component at the base of the eruption sequence. It appears that the rhyodacite made its way to the surface by exploiting the pre-existing andesitic/dioritic intrusion, pushing the crystal-rich contents ahead of it and entraining enclaves from the less crystalline interior. A recent study of crystal zoning patterns in the rhyodacite concluded that the Minoan magma reservoir experienced a spurt of high-flux growth during the century to months prior to eruption onset, due to recharge by large volumes of principally silicic magma. However, eruption finally occurred only once the rhyodacite encountered a suitable pathway to the surface, provided by the mushy Ba-rich intrusion. Either (1) a dyke of andesite feeding the Ba-rich intrusion intersected the main magma chamber, or (2) the main magma chamber inflated under the influx of silicic melt until it intersected the Ba-rich intrusion. The andesites lubricated ascent of the rhyodacite, leading to eruption.

The other side of caldera unrest: why do caldera subside?

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Calderas are known for their restless behavior: remarkable ground deformation is commonly observed during non-eruptive periods, sometime accompanied by seismicity and by significant changes in the chemistry and flow rate of discharged fluids. Uplift phases usually draw attention, as they may be due to shallow magma intrusion, and could therefore prelude to eruptive activity. However, the peculiar feature that characterizes calderas since their very formation is subsidence. Generated by a syn-eruptive collapse of the magma chamber roof, calderas commonly feature a long-term, secular subsidence, that is usually ascribed to magma cooling and contraction and/or to compaction of the soft volcanic deposits. Over a shorter time scale, subsidence may follow episodes of volcanic unrest, as a result of either magma movement or due to the discharge of volcanic gases. Despite its common occurrence and its relevance in the caldera evolution, a systematic assessment of the processes that could drive and explain caldera deflation is still missing. In this work we focus on the secular evolution of the Campi Flegrei caldera. Thanks to the presence of urban settlements along the sea shore, dating back to Roman times, this caldera is a unique site to evaluate the time scales associated with uplift and subsidence phases. Based on this formidable benchmark, we review the geological processes that may be responsible for subsidence, searching for time scales and magnitudes of displacement that are consistent with the available constraints. We believe that a comprehensive analysis that considers all the aspects of ground motion could provide a better image of the deep phenomena that fuel the caldera restless activity.

Caldera resurgence during magma replenishment and rejuvenation at Valles and Lake City calderas

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A key question in volcanology is the driving mechanisms of resurgence at active, recently active, and ancient calderas. Valles caldera in New Mexico and Lake City caldera in Colorado are well-studied resurgent structures which provide three crucial clues for understanding the resurgence process. (1) Within the limits of $^{40}Ar/^{39}Ar$ dating techniques, resurgence and hydrothermal alteration at both calderas occurred very quickly after the caldera-forming eruptions (tens of thousands of years or less). (2) Immediately before and during resurgence, dacite magma was intruded and/or erupted into each system; this magma is chemically distinct from rhyolite magma which was resident in each system. (3) At least 1 km of structural uplift occurred along regional and subsidence faults which was closely associated with shallow intrusions or lava domes of dacite magma. These observations demonstrate that resurgence at these two volcanoes is temporally linked to caldera subsidence, with the upward migration of dacite magma as the driver of resurgence. Recharge of dacite magma occurs as a response to loss of lithostatic load during the caldera-forming eruption. Flow of dacite into the shallow magmatic system is facilitated by regional fault systems which provide pathways for magma ascent. Once the dacite enters the system, it is able to heat, remobilize, and mingle with residual crystal-rich rhyolite remaining in the shallow magma chamber. Dacite and remobilized rhyolite rise buoyantly to form laccoliths by lifting the chamber roof and producing surface resurgent uplift. The resurgent deformation caused by magma ascent fractures the chamber roof, increasing its structural permeability and allowing both rhyolite and dacite magmas to intrude and/or erupt together. This sequence of events also promotes the development of magmatic-hydrothermal systems and ore deposits. Injection of dacite magma into the shallow rhyolite magma chamber provides a source of heat and magmatic volatiles, while resurgent deformation and fracturing increase the permeability of the system. These changes allow magmatic volatiles to rise and meteoric fluids to percolate downward, favoring the development of hydrothermal convection cells which are driven by hot magma. The end result is a vigorous hydrothermal system which is driven by magma recharge.

Caldera unrest at Taupo Volcano, New Zealand: intensity, impacts and mitigation

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Taupo Volcano is considered one of the most active caldera centres in the world. Its last eruption occurred in 232 AD, in a 35 km³ volume (DRE), rhyolitic, caldera-forming eruption which devastated a large portion of the Central North Island of New Zealand. Prior to eruptions volcanoes exhibit signs of unrest commonly in the form of seismicity, ground deformation or hydrothermal or geochemical changes. The integration and interpretation of these phenomena is considered key to eruption forecasting. The majority of unrest episodes at calderas do not result in eruptions leading to potential "false alarms". Identifying the range of possible future multi-parameter unrest activity based on previous events at the volcano contributes to eruption forecasting.

This research involves a historical chronology of all volcanic activity observed at Taupo Caldera since written records began in the 1850s. Document analysis of newspaper articles, local and scientific literature, correspondence and analysis of monitoring data contributed to the dataset. From this, a catalogue was created summarising 91 episodes of heightened activity.

The wide range of intensity of episodes found in this research questions the definitions of the terms "background" and "unrest" commonly used in the literature. The complete range of activity at any type of volcano seen during periods of quiescence (including caldera unrest) is described here as Non-Eruptive Volcanic Activity (NEVA).
The physical impacts of NEVA at Taupo Caldera include subsidence of 3.7 m over a period of months, seiches in the lake which fills the caldera and episodes with an average of 100 earthquakes felt per day. Societal impacts reported include anxiety, self-evacuations, damage to infrastructure and a perceived impact on the local and regional economies.

In order to help mitigate the impacts of future caldera unrest in New Zealand, a Caldera Advisory Group has been formed. This is a multi-agency strategic planning group organised by regional councils. Other members include the Ministry of Civil Defence and Emergency Management, local councils and GNS Science. Outputs of this Group include a caldera unrest information sourcebook for non-scientists, and a scenario for planning purposes based on the past NEVA at Taupo Caldera.

The Oskjuvatn caldera North Iceland revealed by detailed bathymetric study

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The Dyngjufjoll volcanic complex has an area of some 400 km2 with a maximum elevation of 1,516 m a.s.l., rising 600 to 800 m above the surrounding highland plateau. The oldest exposed parts of the centre, dominantly basaltic in composition, were formed in subglacial and subaquatic eruptions and deposited as hyaloclastites forming the elevated topography. The volcanic centre is surrounded and partially covered by extensive Holocene lava flows erupted from fissures striking NE-SW. There are at least 4 if not 5 calderas that have developed within the volcanic complex during the past 700 ka. By far the largest and most prominent one is the 45-km2 Askja caldera centrally located within the Dyngjufjoll massive, thought to have formed some 10 ka ago. The floor of the caldera is covered with Holocene lavas which issued from fissures mostly along the caldera rims. The youngest caldera is the nested Oskjuvatn caldera formed in the southeast corner of the main Askja caldera during and after the 1875 A.D. eruption. The Oskujvatn caldera is a lake-filled caldera, which has hampered its geological observation up to now. The caldera is 5 km in diameter (area, 18 km2). The maximum depth of the caldera lake is 205 m in the western half of the caldera. Rims of the caldera rise >60 m above the lake surface, indicating a total depth of no less than 260 m for the structure. Maps made by a Danish expedition in 1876 show that location of the deepest part of the caldera has changed. We also observe several eruptive vents that are unaccounted for, both along the main ring fault and within the eastern half of the caldera. Several large geothermal areas are observed on the bottom of the caldera, one in the west below the Myvetningahraun lava flow and the other in the east in relation to, until know, unknown volcanic vent. Analysis of historical accounts shows that the Oskjuvatn caldera was not fully developed until 1932 (Hartley and Thordarson, 2012), while internal unconformities in the 28-29 March 1875 tephra deposit indicate that the initiation of the collapse coincides with onset of the eruption. This suggests that the formation of the Oskjuvatn caldera took more than 50 years. These observations along with the new bathymetric map of the Oskjuvatn caldera will be presented and discussed.

Investigating the state of the reservoir below the Rabaul caldera (Papua New Guinea)

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The area of Rabaul (Papua New Guinea) consists of at least seven - possibly nine - nested-calderas that have formed over the past 200 ky. The last caldera-forming eruption occurred 1400 y BP, and produced about 10 km3 of crystal-poor, two-pyroxene dacite. The most recent major explosive activity in the area was preceded by decade-long unrest (starting in 1971) until the simultaneous eruption of Vulcan and Tavurvur, two vents on opposite sides of the caldera (September 19th, 1994). Ten years prior to the eruption, a peak of seismic activity and deformation occurred, which promoted part of the local population to evacuate spontaneously. The recent history at Rabaul is therefore a perfect example of the complexity and problems associated with volcanic unrest and activity in a caldera setting. In addition, it is possible to study the deposits of the eruptions that ensued from the prolonged period of seismic and deformational activity, and therefore gain insights into the processes responsible for the unrest. The 1994-to-present deposits show clear signs of mixing/mingling between basaltic and dacitic magmas, in the form of banded pumices, quenched mafic enclaves, and hybrid bulk rock compositions. We estimate that at least 20-35 wt% basalt has mixed with the resident silicic magma. The time scales of mixing indicated by kinetic modeling of plagioclase zoning suggest that replenishment events coincide with the main period of unrest (1971 to 1985). We use a petrological, geochemical, and numerical modeling approach to investigate the current state of the main reservoir and its evolution since the last caldera-forming eruption. Our working model is that basaltic melts ascend to shallow crustal levels before intruding a main silicic reservoir beneath the Rabaul caldera. Storage depths and temperatures estimated from mineral-melt equilibria and rock densities suggest that basalts ascend from ca. 20 km (600 MPa) to ca.7 km (200 MPa) and cool from ca. 1150-1100 C before intruding a dacitic magma reservoir at ca.950 C. Depending on the state of the reservoir and the volumes of basalt injected, the replenishing magma may either trigger an eruption or cool and crystallize. Preliminary geochemical modeling suggests that the caldera-forming dacitic magma could be generated by fractional crystallization of the basaltic magma at shallow depths (ca.7 km, 200 MPa) and under relatively dry conditions (less than 3 wt% H_2O). We use evidence from major and trace element geochemistry, volatile contents, and the comparison of successive eruptions since 1400 y BP to address the question of whether another potentially caldera-forming magma is presently brewing beneath Rabaul.

Magmatic-tectonic triggers leading to the eruption of multiple isolated magma batches and twin caldera collapse in the Taupo Volcanic Zone, New Zealand

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Calderas, their associated structures, and the geometry of their pre-collapse magma reservoir(s) have been the subject of much scientific intrigue, largely because they represent the largest scale of volcanic eruptions and our knowledge has only been gleaned from ancient examples. However, detailed field, analogue, and petrochemical studies of several calderas reveal an often complex arrangement of magma bodies that are chemically distinct from each other. In addition, the arrangement and geometry of these magma bodies can be dictated by regional tectonic structures that are activated during eruption and collapse. Here, we present new petrochemical evidence for a complex subvolcanic plumbing system including multiple juxtaposed magma bodies that erupted over a remarkably short timeframe to form twin calderas 30 kilometers apart.

The Rotorua and Ohakuri calderas in the central Taupo Volcanic Zone (TVZ) formed 240 ka with the eruption of >245 km3 rhyolitic magma associated with the Mamaku and Ohakuri ignimbrites, respectively. As a consequence, a large volcano-tectonic depression spanning the area between the two calderas formed. New pumice glass and melt inclusion data (combined with the existing bulk-rock and mineral chemistry) supports a petrogenetic model for six different magma batches extracted from the same source region, i.e. a laterally extensive and continuous intermediate mush zone beneath the Rotorua and Ohakuri calderas. Minor geochemical differences in the batches, including fluid mobile elements U, Cs, and Li and volatiles (CO2 and H2O), suggest different extraction conditions for the emplacement of the magma batches. However, combining the chemistry with the timing of eruption for each batch (recorded in the deposit stratigraphy) suggests a more tantalising picture for the spatial distribution of the magma batches in the upper crust and a close interplay between tectonics, magmatism and volcanism. In particular, the initial plinian airfall eruption from Ohakuri erupted simultaneously with the Mamaku ignimbrite from Rotorua and they share a similar trend in Cs and Li concentrations, and CO2 values that suggest, if volatile saturation was reached, melt inclusion entrapment at pressures ranging from 75 to 150 MPa. The chemistry suggests that the magma batches for the earliest eruptions may have been fed by a connected rhyolitic dyke on the western margin of the large volcano-tectonic depression. An elongated rhyolite dome with the same 240 ka age and same chemistry also lies on the western margin of the depression between the two calderas; further supporting the idea of a laterally extensive dyke. The evacuation of these magmatically linked melt batches via a laterally extensive dyke could have initiated rupture of regionally linked faults enough to trigger the eruption of the chemically distinct magma batches associated with the Ohakuri ignimbrite and collateral subsidence of the area between the two calderas.

First recorded eruption of Nabro volcano, Eritrea, 2011

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The 2011 eruption of Nabro began with few detected precursory signals. At the time there was no seismic network operating in Eritrea. Nevertheless a rapid response on the ground led to timely evacuation of settlements within the two calderas and on the flanks of the volcano. Several thousand people were displaced and cared for in temporary camps in the region. In broad terms, Nabro is sited in the extensional zone of Afar, close to the Mesozoic crustal block of the Danakil Alps. It reaches a maximum elevation of over 2200 m above sea level, and has an 8 km wide summit caldera and associated ignimbrites. The 2011 eruption began on 12 June following intense seismicity. It is the first eruption of Nabro on record, highlighting the potential of caldera systems to erupt with limited warning. It is also the first seismicity of note instrumentally recorded in this part of the rift. Remarkably, the Nabro plume significantly perturbed stratospheric aerosol optical depth reflecting a sizeable SO2 emission (of order 1.5 Tg). We present here a preliminary synthesis of the nature and causes of the eruption based on multiple observations (satellite remote sensing, seismology, infrasound records, ground observations, and petrological characterisations).

Episodes of magmatic fluid injection into hydrothermal systems and caldera unrests. The case of Campi Flegrei (Italy)

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The isotopic signatures of many fumaroles from volcanoes, and in particular from calderas, indicate that the feeding hydrothermal systems are recharged by a mixture of shallow waters, of meteoric or marine origin, with magmatic fluids. In the few cases where long time series of chemical and isotopic compositions of the fumarolic vents are available, the data suggest that the mixing processes occur during short periods during which large amount of magmatic fluids are injected in the hydrothermal system. In this frame Campi Flegrei is the best studied case. Since 1980, the fumarole compositions and their variation in the time are known together with the seismic activity and the ground deformation of the caldera. On the base of an accurate analysis of the long geochemical time series, i.e. variations in the main component of the fumaroles as well in the minor gas species and in their isotopic composition, we recognised that thirteen episodes of injection of magmatic fluids into the hydrothermal system occurred from 1980 to 2012. The sudden arrive of the magmatic fluids causes the pressurization of the hydrothermal system and in turn pulsed ground uplift episodes and earthquakes, a process which well explain the correlation in the time among geochemical and geophysical signals. The process was simulated with a physical numerical model able to treat energy and fluid dynamics in a hydrothermal system characterised by bi-phase (vapor and liquid) and bi-component (water and carbon dioxide) fluids. The model was constrained by the flux of CO2 and of thermal energy measured at the surface as well as by the rock properties of the volcanic products filling the caldera. The results indicate that each episode of magma degassing involve an amount of fluids of the same order of magnitude as that involved in medium-small size eruptions. Furthermore the cumulative curve of the masses injected in each episode shows an inversion in 2000 which divides a preliminary period of decrease in the flux of magmatic fluids from the present phase of increasing activity, suggesting the beginning of a new unrest phase at Campi Flegrei. The approach used here is potentially a powerful tool for quantifying the evolution of hydrothermal systems undergoing magmatic fluid injections. This opens the door to accurately detecting and correctly interpreting early signals of volcanic unrest in potentially hazardous caldera settings.

Mapping long-term vent opening in a caldera setting with uncertainty estimation: application to Campi Flegrei caldera (Italy)

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Campi Flegrei is an active volcanic area located in the Campanian Plain, along the Tyrrhenian margin of the southern Apennines (Italy), dominated by the formation of a 12 km large, resurgent caldera. The great majority of the eruptions have been explosive, variable in magnitude and intensity and characterized by the generation of remarkable ash fallout and pyroclastic density currents deposits. In this study we present results of field work and statistical analysis of past eruptive activity aimed at producing long-term probabilistic maps of vent opening at Campi Flegrei. Field work was focused on the structural and morphological nature of the caldera and particularly on the reconstruction of the location of past eruptive vents as well as of main faults and eruptive fissures formed in the last 15 kyr of activity. The statistical analysis performed accounted for the spatial distribution of past vent locations but was flexible enough to incorporate the heterogeneous geological information available, such as the density of faults/fissures or the clue of possible past vents hidden by the more recent activity. One key objective of the analysis was to directly incorporate into the maps the main uncertainties affecting the system. This was done by adopting appropriate density distributions of the probability of vent opening of the different areas of the caldera and by relying on expert judgement. Results allowed to quantify the influence of the different theoretical assumptions and sources of uncertainty on the long-term mapping of vent opening. The distributions obtained represent the starting point for the production of long-term ash fallout and pyroclastic density hazard maps at Campi Flegrei caldera.

The Campi Flegrei Deep Drilling Project: using borehole data to model caldera unrest

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Campi Flegrei is a densely populated, active caldera immediately west of Naples in southern Italy. It has a well-documented history of unrest since Roman times, involving caldera-wide uplift and subsidence with peak vertical movements on the order of 10 m. Geodetic data suggest that the unrest has been driven by changes in pressure at depths of about 3-4 km or less. The pressure change has been attributed to the intrusion of magma or to disturbances in geothermal fluids within the shallow crust. A major goal is to determine the relative contribution of each process, because the potential for eruption is significantly enhanced if magma movement emerges as the primary component.

Uncertainties in the physical properties of crustal rock at depth are a key source of ambiguity in interpreting unrest. Of particular interest are better-constrained values of permeability and rock strength, because these parameters (1) determine the efficiency of fluid flow through geothermal systems and (2) constrain the stresses required for magma intrusion. Reducing the uncertainties is a primary goal of the Campi Flegrei Deep Drilling Project (CFDDP), which is supported by the International Continental Scientific Drilling Program (ICDP). A 500-m deep pilot hole was drilled from July to December 2012, ahead of the main 3.5-km borehole scheduled for the next year.

An adapted leak off test (LOT) was performed along an 84-m free section at the bottom of the borehole, in order to measure the in-situ permeability and tensile strength of crustal material (predominantly grey tuff). The permeability test was performed by injecting water at pressures greater than hydrostatic and then recording the pressure decrease with time after the water pump had been switched off. The measurements yielded average permeabilities of $2x10^{-13}$ to $4.3x10^{-13}$ m^2. These values are larger than those obtained from laboratory samples (about 0.01-0.1 m in dimension) and represent the effective permeabilities at the length scales of at least 1-10 m that are appropriate for modelling the large-scale flow of geothermal fluids. The associated values for bulk tensile strength were 5.7-6.4 MPa. Such values are typical of the shallow crust and provide upper limits on the overpressure in a magma body than can be supported by surrounding rock without inducing bulk failure and the possibility of magma escape.

Contemporaneous eruptions at 4.0 ka from 5.4 km apart vents within Campi Flegrei caldera (Southern Italy): a comparison to Rabaul caldera

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The Campi Flegrei caldera is a collapsed structure mainly resulting from the Campanian Ignimbrite (39ka) and the Neapolitan Yelow Tuff (15ka) eruptions. Post caldera activity has occurred at vents scattered within the caldera with eruptions concentrated in relatively short time periods (volcanic epochs) alternating with millennia-lasting volcanic quiscence. The eruptions at different vents within each epoch have been classically considered to occur in sequence. However, Isaia et al (2009) documented for the first time that the eruption occurred at Averno and Solfatara craters, situated 5.4 km apart, actually occurred, at least in part, simultaneously.

In this study we describe and analyses in detail a key tephra section located about 1.5 km NW of the Solfatara crater where the deposits originated from the two vents are interstratified. The sequence, about 1m thick, consists of almost plane-parallel alternatng green and pink colored ash beds that overlie a layer of discontinuos pumice bombs. The green-colored ash beds forms more than half of the succession, the pink-colored ash consists of several discrete mm- to cm-thick beds. SEM ash clasts characterization coupled with EDS analyses of fresh glass shards and pumice matrix, indicate that the fine-grained green-colored ash, consists of hydrothermal altered materials erupted by the Solfatara crater. In contrast, the pink-colored ash consists of fresh glass shards with composition range similar to the Averno eruption products. In particular the comparison of the glass chemestry with the one made on the proximal eruptive sequence of the Averno eruption (Formentraux et al., 2012) enabled us to assess that the studied section mirrors the entire Averno sequence and that the bomb layer at the base was erupted during the early plinian phase of the eruption.

We conclude that the Averno and Solfatara eruptions started and ended almost contemporaneously. The comparison with the Tavurvur and Vulcan pyroclastic sequences produced during the very recent eruptive vents occurred in 1994 at the Rabaul caldera shows striking similarities suggesting that the occurrence of contemporaneous eruptions at calderas might be more frequent than previously thought. Identifying these type of event can enhance the volcanic hazards assessment and the expected future eruptive scenarios within active calderas.

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Is fluid injection the predominant source of Campi Flegrei (Italy) unrests? Clues from the comparison of inflations and deflations.

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The Campi Flegrei (CF) caldera is a high-risk volcanic area located West of Naples (Italy). CF is generally uplifting since a few years, after a 20-year-long subsidence started at the end of the recent 1982-84 unrest (maximum uplift about 180 cm). Few mini-uplifts with subsequent total or partial recoveries are superimposed on the multiannual trend. While mini-uplifts are usually ascribed to changes in the sub-surface hydrothermal system or injections of magmatic fluids, a long-standing controversy characterizes the interpretation of the 1982-1984 uplift episode, both in the source geometry and unrest cause (intrusion of magma, injection of magmatic fluids, or instability of the hydrothermal system).

As regards the 1982-1984 uplift, deformation data (obtained from leveling and triangulation surveys) seem consistent with different source models, like pressurized ellipsoidal cavities, mixed-mode faults, fluid injection. As a consequence, deformation data seem unable to resolve the above-mentioned controversy. However, numerical models of fluid injection indicate strong time variations in the surficial deformation pattern during inflation and even more between inflation and deflation.

Here we compare surficial deformation patterns of the major mini-uplifts and subsequent recoveries, the 1995-2000 subsidence, and the 1982-1984 unrest. We use SAR data (ENVISAT ascending and descending orbits, courtesy of IREA/CNR, Naples, Italy) between 1995-2010, and leveling and triangulation (EDM and angular) data for the 1982-1984 unrest. Horizontal displacements from triangulations are given with respect to a local not-fixed coordinate system whose origin coincides with a reference triangulation monument and whose y-axis points toward a second one. Since the overall deformation pattern is always nearly axial, we have searched for a roto-translation capable to make the 1982-1984 horizontal displacements radial, thus transforming displacements with respect to the local coordinate system to absolute displacements.

We find that all the overall deformation patterns, both uplifts and subsidences, coincide within errors and noise until 2007. The only evident difference between the 1982-1984 unrest and the subsidence phase relates to a small area (Solfatara) rich of fumaroles. Although we cannot reject fluid injections, the distinct constancy of the surficial deformation pattern may rule out their predominant role as source of deformation at CF, maybe apart from Solfatara. After 2007 the deformation pattern seems to consist of the "usual" pattern and an "anomalous" side uplift, whose origin is under investigation.

Changbai volcano: seismic tomography, origin and East-Asia tectonics

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Recent high-resolution seismic tomography revealed a prominent low-velocity anomaly from the surface down to 410 km depth beneath the Changbai volcano and a broad high-velocity anomaly in the mantle transition zone under East Asia (Zhao et al., 2004, 2009; Lei and Zhao, 2005). Focal-mechanism solutions of deep earthquakes indicate that the subducting Pacific slab under the Japan Sea and the East Asia margin is subject to compressive stress regime (Zhao et al., 2009). These results suggest that the Pacific slab meets strong resistance at the 660-km discontinuity and so it becomes stagnant in the mantle transition zone under NE Asia. The upper mantle under NE Asia has formed a big mantle wedge (BMW) above the stagnant slab (Zhao et al., 2007, 2011; Zhao and Liu, 2010). The BMW exhibits low seismic-velocity and high electrical-conductivity, which is hot and also wet because of the deep dehydration reactions of the stagnant slab and the convective circulation process in the BMW. These processes lead to the upwelling of hot and wet asthenospheric materials and thinning and fracturing of the continental lithosphere as well as the formation of the active intraplate volcanoes in NE Asia. Therefore the active Changbai intraplate volcanism is not related to a deep mantle plume but is caused by the plate tectonic processes in the upper mantle and the mantle transition zone. A better understanding of these processes can be achieved by deploying a network of seismic stations on the Korea Peninsula and Japan Sea to determine higher-resolution mantle tomography under NE Asia in addition to conducting other geophysical and geochemical investigations of the region.

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A preliminary evaluation of the impact of pyroclastic flows using TITAN2D at the Baekdusan volcano according to three different scenarios

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The Baekdusan volcano was formed by three stages of activity: (a) a basalt shield(aging between 2.77 and 0.31Ma), (b) a trachytic comendite stratocone(aging between 1.19 and 0.02 Ma), (c) a trachyte-comenditite ignimbrite deposits(aging between 20 ka up to the present). Volcanic seismicity, ground deformation, and volcanic gas geochemistry yields new evidence for magmatic unrest of the volcano between 2002 and 2006. The monitoring data suggest that the Mt. Baekdusan is a potentially active volcano and close attention is needed. One of the possibly treat of this volcano is the pyroclastic flow volcanic hazard. In order to evaluate the pyroclastic flow emplacement on this hazardous volcano, we use Titan2d code. It is based on a depth-averaged model for an incompressible granular material, governed by Coulomb-type friction interactions. The governing equations are obtained by applying conservation laws to the incompressible continuum, and then taking advantage of the shallowness of the flows to obtain simpler depth-averaged representations. The motion of the material is considered to be gravitationally driven and resisted by both internal and bed friction forces. The resulting hyperbolic system of equations is solved using a finite-volume scheme with a second-order Godunov solver. The DEM file (UTM easting, UTM northing and elevation in meters) must be properly configured to operate with TITAN2D through the use of Grass GIS Software. The other input parameters used are: volume(5-10x107 m3, 1x109 m3, 2x1010 m3) of a vertical cylinder pile(maximum height, major and minor axes), center of initial volume(the location of the initial pile center are the vents of the 1903, 1702, 1668, Millennium eruptions), several orientation angle of the initial pile were selected, internal friction angle(25-30 degree), bed friction angle(16-25 degree).The pyroclastic flow run-out calculated in the field are small(3000 m, 1903 eruption) intermediate(5000 m, 1668-1702 eruptions), large(6-70000 m, Millennium eruption). The initial velocities(m/s) range from 50(1903 eruption) to as high as 300(Millennium eruption). The input parameters have constructed three scenarios(1903, 1702, 1668, Millennium eruptions) following the recent volcanic history of Baekdusan volcano. These eruptions brace all the possibly explosive eruptive scenarios that can occur at Baekdusan volcano in the future. Preliminarily, the 1903 type scenario has been performed, according to the vent location, the flow moves in diverse direction(NE, SE) with a thickness of 3 m, if the vent is center of the caldera the flow fills the caldera with a thickness of 5 m. The modeling of the other two scenario are in progress.

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Eruptive history of Tianchi Volcano, Changbaishan, northeast China: Process and hazard

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Tianchi volcano, also known as Changbaishan or Baitoushan volcano, on the China-North Korea border is a historically active polygenetic central volcano, which consists of three parts: a lower basaltic shield, an upper trachytic (and comendite) composite cone, and young comendite ignimbrite flows as shown in the table. The Millennium Eruption occurred between 938 and 946 AD. Three have been some additional, small "historical" eruptions in the last three centuries.

Between 2002 and 2005, unrest signals including seismicity, deformation, and the helium and hydrogen gas contents of spring waters increased markedly, causing a regional concern. We attribute this unrest event to magma recharge or volatile exhalation or both at depth, followed by two episodes of addition of magmatic fluids into the overlying aquifer without a phreatic eruption. The estimated present magma accumulation rate is rather low to account for the 2002-05 unrest but there are some indications for magma mixing process happened beneath the volcano in the past. The most serious volcanic hazards neat Tianchi Volcano are related to ignimbrite-forming eruptions and lahars.

Stages; Formation and Age; Lithologies

Historical or post-ignimbrite eruptions;

Liuhaojie tuff ring (1903 AD?); Comendite pheatomagmatic layers

Wuhaojie (1702 AD?); White gray comendite fine glass ash

Baguamiao (1668 AD?); Dark gray trachyte ignimbrite and pumice

Late: Ignimbrite-forming;

Millennium eruption (946 939 AD); White gray comendite ignimbrite and air fall pumice and B-Tm ash with minor trachyte ignimbrite and air fall pumice

Qixiangzhan (17 Ka); Comendite lava and pyroclasts

Tianwenfeng falls (25 Ka); Yellowish fallouts on the rim and B-V tephra layer

Middle:Composite cone construction;

Baitoushan 3 (0.02-0.22 Ma); Trachyte and comendite lava

Baitoushan 2 (0.25-0.44 Ma); Trachyte with Laohudong basalt

Baitoushan 1 (0.53-0.61 Ma); Trachyte

Laofangzixiaoshan (0.75-1.17 Ma) Basalt

Xiaobaishan (1-1.49 Ma); Trachyandesite and trachyte

Early: Shield-forming;

Baishan (1.48-1.66 Ma); Basalt

Toudao (2.35-5.02 Ma); Basalt

Naitoushan (15.6-22.64 Ma); Basanite, Basalt

Major historical eruptions of Tianchi volcano, Changbai Mountain, NE China

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Tianchi volcano, is a huge stratavolcano located on the border of NE China and North Korea The Millennium eruption of Tianchi volcnao, erupted at somewhat AD 1000, is one of the world biggest eruptions in the last 2000 years. Historical documents reveal that the last eruption may occurred in about 300 years ago(AD1668 and AD1702). Activity of this volcano is monitored by all modern methods. Potential eruptions of this world most dangerous volcano attract attentions from both the public and the scientific. However, better understanding of the historical eruptions of Tianchi volcano will help us to learn more about the future activity. Here we report our recent studies on major historical eruptions of Tianchi volcano.

Five major eruptions, labeled as T1 to T5, in Holocene have been recognized in Tianchi volcano. The first one eruption, T1, occurred in about 5000 aBP, formed a thick layer of yellow pumice, widely distributed on and around the volcanic cone of Tianchi. The second one, T2, usually known as Qixiangzhan eruption, occurred in 2000 aBP, formed a small lava flow of black obsidian, with limited distribution on the northern peaks of Tianchi. T3 is the famous Millennium eruption, the most important eruptions in Tianchi. Volcanic productions, grey pumice, cover large area from Tianchi volcano to 1000 km eastward of Japan. After the Millennium eruption, several eruptions have been argued in the past few hundreds of years, and two eruptions, T4(red) and T5 (black) have been recognized here. T5 may have a small vent at the water vent of Tianchi crater, and also distributed on the top of Tianchi cone and Bingchang. Mineral assemblage and major element geochemistry of voclanic glass of these historical eruptions have distinguishable features.

Fractional crystallization in crustal magma chamber dominants the nature of major historical eruptions of Tianchi volcano. Typical mineral assemblages of fractional crystallization are alkaline feldspar and hedenbergite, with minor other minerals of fayalite, quartz, apatite and Fe-Ti oxide. E probe data indicate that the historical eruptions have similar mineral chemistry. A simple model have been used to estimate the extent of fractional crystallization. If we take a magma of SiO2 64

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The millennium eruption of Changbaishan volcano in northeast China: High-precision wiggle-match radiocarbon chronology and implications

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The 10^{th} century AD eruption (or so-called millennium eruption) of Changbaishan volcano, located at the border between China and North Korea, is one of the biggest (VEI 7) on Earth over the past 2,000 years. However, the exact timing of the event has been under intense debate for nearly three decades and no unambiguous and consensus radiometric chronology exists for the eruption at present. In this study, we report a new accurate and precise chronology of AD 946 $\pm$ 3 for the millennium eruption, which was derived from radiocarbon wiggle-match dating of a 264-year old tree trunk (with bark) buried in the pyroclastic flow deposits of Changbaishan volcano. High-precision radiocarbon measurements were made on 27 sequentially sampled annual rings of decadal intervals with analytical precision of $\pm$ 25 ^{14}C years, on this 260-year tree-ring sequence that covers three consecutive wiggles around AD 910, AD 785, and AD 730. Since longer dated tree-ring sequence, finer sample resolution and higher ^{14}C analytical precision all facilitate more and tighter tie-points for better WM dating, our new date is believed to represent yet the best high-accuracy and high-precision ^{14}C WM chronology for the Millennium eruption. Moreover, this new age conforms perfectly to the exact date of AD 946 inferred from Korean and Japanese historical documents and therefore should end the decades-long debate about the timing of the eruption. No stratospherically loaded sulfate spike that was likely associated with the eruption is found in the global volcanism record from the GISP2 Greenland ice core, suggesting that the millennium eruption was a Toba-like "ash giant/sulfur dwarf" and thus had much smaller climatic impacts than implied by its magnitude in the northern hemisphere (compared to the climatic impact of the 1815 Tambora eruption that also has a magnitude of VEI 7). Our new chronology will serve as a solid knowledge basis for better understanding of the recurrence interval and eruptive risk of this potentially most destructive volcano in northeast China.

Petrogenetic history of alkali magmatism at Baitoushan/Changbaishan volcano, China/N. Korea

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The Baitoushan/Changbaishan "hot spot" volcano, located along the China/N. Korean border, has erupted a range of magma compositions from trachyte to rhyolite in the last ~20ky. These magmas retain a variety of distinct mineral and melt components that result from the interplay of multiple alkali-rich magmas, including alkali basalts, trachytes, comendites, and a pantellerite. Potential parental alkali basalts, present as satellite cinder cones surrounding the main edifice, are in U/Th and Th/Ra equilibrium suggesting a lack of initial disequilibrium or old ages. In contrast, two younger comendite units, found along the northern ridge of the caldera, both have U/Th disequilibria and one also has Th/Ra disequilibria, attesting to the youthful nature of comendites at this edifice. $^{87}Sr/^{86}Sr$ ratios of individual potassium feldspar crystals are uniform in the younger of these comendites but are variable in the older, which precludes their derivation from the same magma reservoir. In addition, a pantellerite pumice deposit, located to the east of the main edifice, is intermediate in age between the comendites and has U/Th and Ra/Th disequilibria. It contains quartz crystals that have Titanium in Quartz temperatures lower than 700 degrees Celsius and Th/Ra equilibrium probably as a result of remobilization from a cumulate crystal mush. The highly voluminous comenditic Millenium Eruption (~1000CE), for which Baithoushan/Changbaishan is known, retains extensive U/Th and Th/Ra disequilibrium in both whole rocks and minerals, including potassium feldspar and quartz, and zircons and chevkinite crystals with ages of ~10 ka. Minerals have variable Pb isotope ratios suggesting remobilization from a crystalline mush. By integrating Sr, Nd, and Pb isotope ratios and U-series age constraints of minerals and magmas, we will address the petrogenetic history of this active magma system. Where possible, we also evaluate magmatic conditions at which these interactions occurred using Titanium in Quartz geothermometry, thus building an integrated picture of the time and conditions in which magmatic components are assembled in alkali-rich magma systems.

Magma system and its eruption processes of the caldera-forming 10th century eruption of Changbaishan (Baitoushan) Volcano: Inferred from petrological and geochemical characteristics

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The 10th century eruption of Baitoushan volcano forming the summit caldera can be divided into three phases, Phase 1 to 3 in ascending order, with a short dormancy. Although previous studies have considered both Phase 2 and 3 as the 10th century eruption, pumice fall and pyroclastic flow deposits of the Phase 1 are newly recognized in the limited areas. The age of the Phase 1 might be several tens and hundreds years before the 10th century eruption, because there exists thin soil layer between Phase 1 and Phase 3. Juvenile ejecta widely ranges from comendite to shoshonite (SiO2=53-76, Na2O + K2O=6-13). Major ejecta of the Phase 1 and 2 were comendite pumice, whereas those of Phase 3 were trachyte scoria. Based on the distribution of core compositions of phenocrystic minerals in a single sample, chemical trends on oxide-oxide diagrams and Nd isotope ratios, it can be concluded that five magmas were separately present before the eruption, two types of comendite magma with higher and lower Nd isotope ratio (high-Nd and low-Nd CM magmas), two types of trachyte magma with higher and lower SiO2 content (high-Si and low-Si TR magmas) and shoshonite magmas. During the eruption of each phase, magma mingling and mixing of two or three magmas occurred. The 10th eruption began with the withdrawal from Low-Nd comendite (low-Nd CM) magma (Phase 1), and was followed by eruption from another comendite magma (high-Nd CM) after a dormancy (Phase 2). During the later of both phases, mixed magma of comendite magma (low-Nd CM in Phase 1 and high-Nd CM in Phase 2), high-Si TR and shoshonite magmas also erupted. Thus, it could be speculated that the high-Si TR magma associated with shoshonite magma had injected into each comendite magma. These two comendite magmas had been exhausted during the two eruption phases. Thus, low-Si TR magma mainly erupted in Phase 3. The magma was injected by the shoshonite magma to erupt with small amount of remnant comendite and high-TR magmas. It can be concluded that three eruption phases of the 10th eruption were related to withdrawal from isolated voluminous three magmas, two types of comendite and trachyte (low-Si) magmas, respectively. The genetic model of a large silicic magma system must explain the processes producing several distinct silicic intermediate magmas at the same time as in the case of the 10th century eruption of Baitoushan volcano.

Tianchi Volcano Millennium Eruption (VEI 7): differentiation processes and timescale

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Although the first and largest phase of the Millennium Eruption magma was >95% almost aphyric comendite (SiO2 73, Al2O3 >11, FeO*<5), the second phase contains a mafic component that occurs as dark streaks in white pumice and as isolated mafic scoria. This mafic component extends from trachyte (SiO2 65, MgO=0.1-0.5) through trachyandesite (SiO2 60, MgO=1.8-2.7) to trachybasalt (SiO2 50, MgO=4.6). Trachyte is the most common. This mafic component contains diverse glass that is intimately mixed at the mm-scale, and a bimodal mineral population: Fo50-80 and Fo8-11; En31-43 and En14-20; An14-66 and An4-5. Comendite has more differentiated and more uniform mineral compositions. Comendite can be derived from trachyte by about 70% fractional crystallization of Kfs»Cpx>Ilm>Ol and Ap»Chevkinite. The mafic component is slightly more depleted isotopically than the comendite with 87Sr/86Sr and 143Nd/144Nd at least 0.00005 lower and higher, respectively, and 206Pb/204Pb about 0.060 lower, based on bulk pumice analyses. Trace element systematics within both comendites and trachytes demonstrate mixing with something more mafic than either, but relatively little mixing between comendite and trachyte. The comendite magma was already 10-20 Ka old at eruption based on U-Th disequilibria in its trace chevkinites and zircons and 226Ra-230Th equilibrium in bulk comendite pumice. However, the mafic mixing component is younger, with higher 230Th/232Th and greater 226Ra-230Th disequilibrium. Therefore, separate comendite and trachyte bodies resided beneath the volcano throughout the Holocene, and both experienced a major recharge event that triggered the Millennium Eruption. The comendite may have received mostly heat from the recharge event whereas the trachyte mixed thoroughly with the recharging magma.

Changbaishan seismic mornitoring network and recent unrest of the volcano

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Changbaishan volcano is the largest potential eruptive volcano in China.Over 12 years of continuous monitoring of Changbaishan volcano by means of volcanic seismicity, ground deformation, and volcanic gas geochemistry, new evidence for magmatic unrest of the volcano was found during 2002-2005. In this so-called "active period" the frequency of volcanic earthquakes increased sharply accompanied by earthquake swarms. Active period was also accompanied by ground inflation, high values of CO_2, He, H_2, and high ratios of $^3He/^4He$ in volcanic gases released from three hot springs near the caldera rim. The monitoring evidence implies pressurization of the magma chamber, possibly caused by incremental magma recharge. The ground deformation data from both GPS and precise leveling are modeled to suggest the corresponding deformation source at 2-6 km beneath the volcano's summit, where earthquake swarms were detected in 2002 and 2003. Our findings suggest that the magma chamber beneath Changbaishan volcano has waked up and resumed its activity after it has remained dormant since AD 1903.

Changbaishan volcano has remained inactive since 2006, however several abnormal signals have been observed in recent years that need special attention. In 2009, precise leveling measurement both in the north and west slope of this volcano show a change of ground deformation mode from inflation to deflation. The water temperature of Julong hot spring suddenly rose to 77.7℃, about 3℃ higher than in 2010, and this abnormal signal persists to the present. Taken together, all these new phenomena might indicate the beginning of a new "active period". The episodic unrests probably caused by pulse of mantle magma intruding into the upper crust.

The magma unrest process in Changbaishan volcano from 2002 to 2005 might be considered as a long term precursor of the potential eruptive activity. However, earthquake swarms and volcanic tremors have not been observed since 2006, volcanic gas geochemistry also has no obvious abnormal indication, the volcano is still in its inactive period now.

Key words:volcano; volcanic event;earthquake;precursor

Volcano-tectonic evolution from Cretaceous to Paleogene time in SW Japan

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The eastern margin of the Eurasian continent during the latest Cretaceous to Paleogene is characterized by the volcanism associated with cauldron swarms and the related plutonism. The SW Japan block was a part of the Eurasian continental margin in this age. The igneous activity is divided into 4 stages, i.e., stage I (>100Ma), stage II (100-90Ma), stage III (90-80Ma), stage IV (75-50Ma) and stage V (44-30Ma). The cauldrons in stages I - IV is likely to make some clusters along the volcanic front in these stages, while the cauldrons in stage V show en echelon arrangement along the continental margin. This suggests the change of regional stresses during the hiatus of the igneous activity in the early Paleogene (50-44Ma).

The clustering of cauldrons in stages I - IV may indicate a plume head beneath the cauldron swarm along the volcanic front. The accretionary prizm along the outer zone of SW Japan shows that the subducted slab lay beneath SW Japan in that time. A volcanic front ran concordantly with this accretion zone through SW Japan during stage I - IV, and then migrated northward in stage V.

Each cauldron in stage V exhibits an elliptical or elongated polygonal outline. The long and short axes of a cauldron represent the directions of horizontal maximum and minimum compressive regional stresses, respectively. The elongated shape of a collapse caldera, which is topographic expression of a cauldron, presumably reflects regional stresses in the lithosphere as well as the geometry of the magma body.

The cauldrons in stage V show a set of right-handed en echelon arrays oriented at an angle of 18 - 20°to the direction of the volcanic front in this stage. The long axes of some cauldrons, representing the directions of the horizontal maximum compressive stresses, trend to 20°or more anticlockwise to the cauldron array. This orientation indicates that SW Japan in stage V was under left-handed Reidel shearing.

Tectonic regime during stage I - IV was probably characterized by the normal subduction followed by plume ascending along the subducting slab, whereas that in stage V was identified as the oblique subduction yielding the left-handed lateral movement in the overlain lithosphere.

Spatiotemporal variations of geochemical characteristics of volcanic rocks from Aso volcano, SW Japan

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Chemical compositions and isotopic ratios ($^{87/86}$Sr and $^{143/144}$ Nd) for late-Pliocene to Quaternary volcanic rocks in and around Aso area in SW Japan, were determined to reveal spatiotemporal variations of the magma characteristics and a mechanism of magmatic system including large caldera volcano related to super colossal eruption.

In this study, volcanic activities in Aso area are divided to 5 stages depending on ages and characteristics of forms of eruptions. 1) Early pre-caldera stage: HMA (High Mg andesite) (3.9Ma) and High Mg picritic basalt (2.9Ma) are distributed on southwestern somma of Aso caldera. 2) Late pre-caldera stage: Pre-Aso volcanic rocks (Watanabe et al., 1989) exposed on caldera wall and somma (0.9-0.4Ma). 3) Caldera forming stage 1st to 4th: 4 colossal to super colossal eruptions (ca. 270, 140, 120 and 90 ka (Watanabe, 2001)) with voluminous pyroclastic flows including scoria and pumice. 4) Inter-caldera stage: Volcanic activities between colossal to super-colossal eruptions, mainly consisted of andesite lava flows (distributed on somma and outside of caldera). 5) Post-caldera stage: Volcanic activities after Aso-4th (the final caldera forming eruption) within caldera, forming Aso central volcanic cones with basaltic to rhyolitic volcanic products. Although Nekodake volcano is one of the Aso central volcanic cones and some volcanic products were dated as in post-caldera stage, geochemical characteristics are strongly related to volcanic rocks of late pre-caldera stage and basement rocks (granodiorite).

Volcanic products of both inter-caldera and caldera forming stage were characterized by high K2O contents and same REE patterns and isotopic ratios. On the $^{87/86}$Sr-$^{143/144}$ Nd diagram, isotopic data of volcanic rocks in early pre-caldera stage separately distributed in two areas (component A: around (0.7040, 0.51285); component B: around (0.7044, 0.51270) and of both late pre-caldera and post-caldera stage distributed between component A and B along mantle array. Sr isotopic ratios of volcanic products of both caldera forming and inter-caldera stages were distributed in very narrow range (0.7040 - 0.7042). Source materials of volcanic products of each stage are inferred from these results.

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Lateral magma intrusion from a caldera-forming magma chamber: Constraints from geochronology and geochemistry of volcanic products from lateral cones around the Aso caldera, SW Japan

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We investigated the K-Ar ages, and the petrological and geochemical features of lava units from lateral cones (Omine and Akai volcanoes) and lava distributed area around the Aso caldera in central Kyushu, Japan, in order to constrain the spatial range of lateral magma intrusion during the caldera-forming stage. The results of K-Ar age determination showed that most of the analyzed lava units erupted almost simultaneously with the Aso caldera-forming pyroclastic eruptions (266 to 89 ka; Matsumoto et al., 1991). In addition, the petrography, major- and trace element compositions, and Sr isotope ratios of these lava units are indistinguishable from the caldera-forming pyroclastic products. In particular, the decrease in Sr isotope ratios over time observed in these lava units is consistent with that of the caldera-forming pyroclastic products. The contemporaneous activities of compositionally similar magmas inside and outside of the caldera presumably indicate the occurrence of a lateral intrusion of caldera-forming magma, which had accumulated in a huge magma chamber beneath the caldera system. In the Aso volcano, it is thought that a total of 6.3 volume percent of caldera-forming magma migrated more than 20 km from the center of the caldera.

Unusually high-temperature andesitic magma erupted shortly before the Aso-2 pyroclastic flow from Aso caldera, Japan

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Aso Volcano, which is located in central Kyushu, southwestern Japan, is one of the largest caldera volcanoes in the world. The caldera (25 km north-south and 18 km east-west) was formed by four large pyroclastic flow eruptions: Aso-1 (270 ka), Aso-2 (14 ka), Aso-3 (12 ka) and Aso-4 (89 ka). Each pyroclastic flow deposit is divided into several flow units. These flow units were deposited by pyroclastic eruptions which accompanied tephra fall just before and/or after the generation of large pyroclastic flows, except for Aso-4 eruption. In particular, the stratigraphy of Aso-2 eruption deposit is very complicated and the chemical compositions remarkably vary between subunits in the eruption cycle. Andesitic lava flows were generated shortly before the main Aso-2 eruption. Tamaraigawa lava distributed east of Aso caldera and Iwato, Akita and Togawa lavas distributed west. These lavas are nearly aphyric and display textural characteristics similar to pahoehoe lava flows.

Lava compositions, temperatures and viscosities have been investigated. All lavas are phenocryst-poor, consist of two pyroxene andesite and have 61 wt.% SiO_2 except for Togawa lava (58 wt.% SiO_2; Matsumoto, 1974). The magma temperatures were estimated using the two-pyroxene thermometer of Anderson et al. (1983). Five to seven coexisting pairs of pyroxenes were analyzed for each lava. The calculated magma temperatures are 1123±23 ℃ (Tamaraigawa lava), 1081±17 ℃ (Iwato lava), 1061±18 ℃ (Akita lava) and 1045±24 ℃ (Togawa lavas). We calculated the melt viscosity of the Tamaraigawa lava at 1123 ℃ (two-pyroxene temperature) using the model of Giordano et al. (2008). The results show that the Tamaraigawa lava has a viscosity lower than $10^{4.5}$ Pa s (dry case). Dissolution with water further decreases the melt viscosity to $10^{2.7}$ Pa s at 2 wt.% H_2O.

In general, andesitic magmas have eruption temperatures of 900-1000 ℃ and viscosities around 10^8-10^9 Pa s. The andesitic lavas in this study, therefore, had unusually high temperature and low viscosity conditions similar to basaltic lavas. The data are consistent with the textural characteristics of pahoehoe lava flow.

Volcanic history of western margin of Aira caldera based on K-Ar geochronology

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Western margin of Aira caldera consists of the Yoshino-dai plateau with a gentle slope to the west and the northern high volcanic mountain area with up to 550 m height with a steep caldera wall faced to Kagoshima Bay of more than 200 m height. It is the area where the most voluminous volcanic rocks distribute around the rim of Aira caldera as well as the post-caldera Sakurajima volcano. Therefore, it is an important area to understand how the Aira caldera has been evolved.

Systematic K-Ar dating by sensitivity method at Kyoto University and Geological Survey of Japan has been performed to the volcanic rocks distributed in this western margin of Aira caldera. The history of the pre-caldera volcanic activities obtained is as follows: (1) Andesitic magmas erupted at the present high volcanic mountain area in the north of present Yoshino-dai plateau from 1 to 0.7 Ma, then formed the volcanic bodies with up to 550 meters height. (2) Next, dacite erupted at the southeastern side of the above mountain area at 0.5 Ma, besides, subsequently basaltic lavas erupted from the present Kagoshima Bay side, overlied the dacites and had also flown between volcanoes of the high volcanic mountain area and in the Kagoshima Bay. (3) Then, rhyolitic pyroclastic flows and subsequent basaltic lava flows erupted westward from the Kagoshima Bay side again and formed Yoshino-dai plateau from 0.45 to 0.35 Ma. (4) The volcanic body which located in the Kagoshima Bay and erupted magmas westwards through 0.5 to 0.35 Ma had collapsed and disappeared some time after 0.35 Ma. Then the Yoshino-dai plateau and the caldera wall had remained as the foot of the previous volcano as shown in the present time. It was also found that the basaltic magma erupted around Aoshiki which locates in the 10 km north from the Yoshin-dai plateau at 0.08 Ma. This implies that the activity of basaltic magma occurred during the period when the volcanic activity at Aira caldera became more active after 0.1 Ma than before as shown in the multiple pyroclastic eruptions including Aira pyroclastic eruption. The K-Ar ages obtained so far from the whole Aira caldera area implies that the location of volcanic activity had migrated along the caldera rim since 1.5 Ma.

Holocene uplift of Aira caldera, southern Japan

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Aira caldera, accompanied by Sakurajima volcano on its southern rim is filled with sea water, forming the inner part of Kagoshima Bay. Emerged sea-level records, i.e. emerged marine deposits and marine terraces occurring around Aira caldera, provide excellent data for obtaining the Holocene crustal movement of the caldera. We obtained the mode of crustal movement of Aira caldera in the past c. 7,000 years on the basis of the elevations of those marine records and their chronology using C-14 age and tephra beds. The highest sea-level at c. 7,000 years cal BP recognized in the northern to northwestern rim of the caldera, attains more than 10 m above the present sea level. The distribution of the sea-level records clearly indicates upwarping with a center of slightly western part of the caldera. The mean uplift rate, c. 1.4mm/yr and the mode of upwarping nearly coincide with those of the historical uplift associated with the volcanic activities of Sakurajima volcano during the past c. 500 years, suggesting that the Holocene upwarping of Aira caldera reflect the volcanic activities of Aira caldera including Sakurajima volcano. This means that the findings of Holocene crustal movements recorded in the coastal deposits and landforms are important for evaluating the future volcanic activities of Aira caldera and Sakurajima volcano.

Cycles of magma activities leading to catastrophic eruptions in aira caldera in Kyushu, Japan

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Aira pyroclastic eruption (29 ka; 450 km^3), one of the largest caldera-forming events in Japan, was proceeded by continuous tephra eruptions (100–30 ka), and provides a unique opportunity to examine transition of magma reservoir compositions leading to the caldera-forming eruption. We report magma compositions between 100 ka and the present, and propose cycles of magma activities in which the mafic magma activity marks early stage and the felsic one marks late stage, ending with catastrophic eruption. We classified one mafic magma group and two felsic magma groups on the basis of mineral assemblages, group-M (under 59 wt.% SiO_2; <95 ka) containing plagioclase, two pyroxenes and rare olivine, group-F1 (63–70 wt.% SiO_2; 95–85 ka) containing plagioclase, two pyroxenes and hornblende and group-F2 (73–78wt.% SiO_2; 60–30 ka) containing plagioclase, orthopyroxene and quartz. Products of Aira pyroclastic eruption, belong to Group-F2 magma.

Patterns of transition of magma compositions during 100 ky at Aira revealed that Group-M mafic magmas were active before felsic magmas (F1 and F2). Aira pyroclastic eruption marks the final eruptive event of Group-F2 activity. Fukuyama pumice fall eruption, which is the largest eruptive event (about 40 km^3) before Aira event (29 ka), marks the final eruptive event of group-F1 magma activity. Incompatible trace element compositions show that Group-M magma and Group-F2 magma do not represent parent-daughter relationship. Contents of incompatible elements of Group-F2 magma increase with time (SiO_2: 2–4 wt.%; Rb: 5–20 ppm) from 60 ka to 30 ka, to the composition similar to that of Aira pyroclastic eruption. Compositional variations observed among Group-F2 magma are explained by crystal fractionation of the mineral phases contained in the parent magma. Felsic magma similar in composition to Aira pyroclastic products appeared 1,000 years before the event.

Volcanic products from Sakurajima volcano (25.5 ka–the present), show binary magma mixing between basalt and dacite. Their mafic end member is compositionally similar to the Group-M magma which appeared in the first and the second cycles. Neither F1 nor F2 magmas are possible candidates of felsic end member of mixing. It is implied that different felsic end member magma, i.e. F3, exists in magma reservoir beneath the present Aira caldera. Magma activities of Sakurajima volcano, probably forms the felsic stage of the new cycle.

Caldera structure of Izu Oshima Volcano, Japan. revealed by new drilling survey

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Izu-Oshima volcano is basaltic stratovolcano with a summit caldera. The caldera is high gravity anomaly type and the eastern rim is almost buried by the younger deposits. It is thought that this caldera was formed by collapse with steam explosion about 1700 years ago. Some drilling survey, such as Isshiki et.al.(1963) were done in western part of the caldera but there are no survey in eastern part. To investigate the structure of the basaltic caldera, we conducted a new drilling survey of 100m depths in the eastern part of caldera.

The proportion of lava in the core is 42% and pryroclastics is 58%. 7 lava units are found in the lower and the upper part of the core except the 4th unit. Thick volcanic breccia and ash fall deposit with accretionary lapilli are found in 38m to 50m deep. This lithology and stratigraphy is very similar to the products at the time of the latest period of caldera formation. The trace element composition of the lava also have different element ratio above and below this breccia, same as the surface distributed lava, thus it indicates this layer is the latest caldera forming deposits. So, the caldera floor hight is about 400m above sea level, 60m shallower than expected from Isshiki et.al.(1963).

From lithology and ^{14}C dating, the eastern caldera had been in the environment that pyroclastic fall only deposited and lava did not come about 5,000 years ago until several hundred years ago. From these, at least three caldera is assumed in Izu-Oshima volcano, the younger western caldera formed about 1700 years ago and the older western caldera about 5,000 years ago and the oldest eastern caldera. Using the estimated spread of the younger western caldera by this study and the caldera floor altitude by previous research, the volume of caldera filled material is estimated. The estimated volume is about 1.6 km^3 and using the lava-pyroclastic ratio (75:25; Isshiki et.al. 1963), the volume of lava is estimated about 1.2 km^3.

The origin and magmatic evolution of Quaternary lavas of Sakurajima volcano, southern Kyushu Island, Japan: inferred from Geochemical and Sr-Nd-Pb isotopic constraints

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Sakurajima volcano represents a post-caldera volcano linked with the Aira caldera, situating at the volcanic front of the Ryukyu arc, southern end of Kyushu Island, Japan (Fukuyama, 1978), where the Philippine Sea Plate (PSP) is subducting, and is considered to be one of the most suitable volcanoes for studying the links between caldera formation and catastrophic silicic magmatic activity. We collected 25 lava samples, from almost all of the volcanostratigraphic units (Fukuyama and Ono, 1981), for a major and trace element geochemical and Sr-Nd-Pb isotopic petrogenetic investigation of Quaternary lavas of Sakurajima volcano.

The Sakurajima lavas are porphyritic andesites or dacites contains Opx-Cpx-Pl with or without Ol as phenocrysts. The Nb depletion along with enrichments in Rb, K, and Pb show the typical island arc magma characters causing by the addition of aqueous fluids to the mantle wedge. The Sr, Nd, and Pb isotopic compositions plot close to a mixing curve between MORB-type mantle and sediments of the Philippine Sea Plate, (PSP) but displaced a bit towards more radiogenic compositions. Plots of Zr v.s. Nb concentration yield a linear trend that falls on a mixing line between the values for MORB and average continental crust. These observations indicate that the primary source magmas were initially generated by partial melting of MORB-type mantle hydrated by fluids derived from the subducting PSP. The contribution of crustal material during magma evolution is also evident from the Zr/Nb ratios and Sr-Nd-Pb isotopic compositions. The mixing relations of Sr-Nd-Pb isotopic compositions suggest that the sedimentary rocks of Shimanto Group can be a source of the crustal materials. Although most of the major element compositions show a single linear trend on each of the Harker diagrams, two different trends are discernible on each of the P_2O_5, and TiO_2 v.s. silica diagrams, and are subdivided into low-P and high-P geochemical groups. The magma mixing trends of Sakurajima lavas, which seem to be extended from mono andesitic end-member to two different deictic end-members, are observed from the relationships of major element contents and $^{87Sr}/^{86Sr}$Sr ratios. In addition, the low-P versus high-P groups of lavas show distinctive distribution patterns, whereby the high-P lavas are surrounded by low-P lavas in the central to southern parts of the Sakurajima volcano. These observations indicate that mixing of andesitic and dacitic magmas played an important role in the genesis of lavas of Sakurajima volcano, and that multiple dacitic magma chambers with different geochemical characteristics once existed beneath the Sakurajima area at relatively shallow levels in the crust. From the relations between SiO_2 and Sr isotope ratios, an AFC process is required to originate the andesite and dacite end-members.

Near-vent morphology and dispersion timing of the climactic PDC in 7300 BP marine caldera formation of Kikai caldera in southern-off Kyushu Island, through seismic reflection survey

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Kikai caldera (Matsumoto, 1943) is a mostly submerged highly active caldera complex located in the southern Japan 40 km off Kyushu Island. The formation of the Kikai is believed to be responsible for dispersion of Akahoya tephra (Machida and Arai, 1978) in 7300 cal. BP (Fukusawa, 1995). The eruption is characterized by intense earthquakes (Naruo and Kobayashi, 2002), low-aspect ratio Koya-Takeshima PDC (pyroclastic density current; Maeno and Taniguchi, 2007) and tsunami (Geshi, 2009) which were taken place at the climax of the eruption.

We conducted seismic reflection observations in two survey cruises (KT-10-18 and KT-11-11) in 2010 and 2011 using a research vessel Tansei-maru of JAMSTEC (Japan Agency for Marine-Earth Science and Technology). The sound source was a 105+45 cubic inches G-I gun with 10 seconds of shot interval, and a 48-channled 1.2 km-length streamer cable was used for acquisition. Totally 24 profiles were obtained with the speed of 4 knots.

1. Possible climactic PDC deposits

Facies in Kikai area show clear distinction between caldera outskirts, caldera basin, and central rise of the caldera. At the caldera outskirts, there is a thick (around 100 m) acoustically chaotic layer named A3 in our interpretation that alike to other presumed PDC-originated deposits (e.g. Lebas et al., 2011). The layer is covered by some intensively stratified deposits except on the southern steep slopes. In contrast with outskirts however, equivalent considered layer in the caldera basin shows acoustic transparency with slight stratification within it, and the bottom terrain of it marks major unconformity. Neither of such characteristic layers was observed at the center of the caldera where large topographic rise exists.

2. Intrusive structure along the caldera-rim

Volcanic bodies are distributed along the caldera-rim. The largest one at the southeastern end has 2.5 km wide, and the rolling-up horizons beneath of it indicate it occurred just before the climactic dispersion. Presence of such bodies make difficult to evaluate caldera displacement however, it reaches 400 m in maximum at the rim of east to southeast.

3. The timing of the climactic dispersion and caldera collapses

Both caldera displacements and inner fractures seem to cut every deposit at every direction, therefore the caldera collapse should be occurred enough after the climax of the eruption. Enigmatic shortage of the talus deposits may reflect the subsidence and opening of the fractures happened gradually.

Frequency of a caldera forming eruption occurred in the Kyushu Island on the basis of the high-resolution tephra stratigraphic record in the Kinki district, central Japan

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Extremely a large-scale explosive eruption, for example a caldera forming eruption, it is sometimes described that such eruption occurred once every 10,000 years. We have been constructed the high time resolution tephra stratigraphic record for Pliocene to Holocene strata in Japan.

A framework for the Pliocene to Holocene tephra stratigraphy in the Kinki district has been established by litho-stratigraphy of the Plio-Pleistocene Osaka Group in and around the Osaka Plain, in addition, by using a number of drilling cores sediments in the Osaka Group and from Lake Biwa. The Osaka Group is mainly composed of fluvial sand, gravel and silt intercalated with twenty-one marine clay beds and over eighty tephra beds. It is especially significant that marine clay beds had been deposited by the corresponding sea level change of the glacial / interglacial cycles. Depositional age of the Plio-Pleistocene tephra beds is determined by a combination of lito-, bio- and magneto-stratigraphy and radiometric age of tephra beds. In particular, staratigraphic positions of tephra beds in the past one thousand three hundreds years is accurate as the stratigraphic sequence because of corresponding the twenty-one marine clay beds to the Oxygen Isotope Stage 37 to Stage 1.

Most of the tephra beds can be individually traced to their source volcanoes based on the volcanic glasses chemistry using the microprobe (EDS) analysis and petrographic properties. As a result, we are identified nineteen co-ignimbrite ash beds during the last 130,000 years. these tephra beds have been mainly derived from Quaternary caldera volcanoes in the Kyushu district, named as the Shishimuta, Aso, Kakuto, Aira, Ata, and Kikai calderas. The excellent tephra stratigraphic record also shows the relation of the stratigraphic positions to the Oxygen Isotope Stage. In short, a many of the co-ignimbrite ash beds have emplacement at the low sea-level stand, and it is possible that the timing of eruption is related to local tectonics and hydro-isostatic stress in the upper crust corresponding to the sea level changes.

Modern iron sedimentation and hydrothermal activity at post Kikai Caldera volcano in Satsuma Iwo-Jima, Kagoshima, Japan: To understand modern bedded iron formation at shallow hydrothermal environment

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Satsuma Iwo-Jima Island at northwest limb of the Kikai Caldera was located 38 km south of Kyushu Island, Japan. Nagahama Bay in the island took on reddish brown color and high density iron-oxyhydroxides seawater which is formed by the neutralization of ferrous iron in acidic hot-spring. After dredging work at 1998, iron-oxyhydroxide sediments have accumulated about 1 to 1.5 meter on the bottom of this bay. For estimate the amount of iron material discharge and sedimentation history, we collected 13 core samples from this bay and form cross section in this bay. The stratigraphy in these cores well preserved volcanic activity and weather condition such as storm, heavy rain and calm condition from comparison meteorological data. Also cross section and column show elucidated sedimentation period of characteristic key beds and calculated sedimentation rate of iron-oxyhydroxides.

Cores contains iron-oxyhydroxides muds layers, three thick tuff beds and a thick sandy mud bed. Iron-oxyhydroxides mud consisted minor volcanic glass and mainly 1 micro meter to 100 nano mater Fe mineral. Tuff beds were composed of volcanic glass and Si-bearing minerals. Sandy mud bed was essentially a mixture of rock fragments, volcanic glass and fine reddish-brown grains. Comparison with this stratigraphy and meteorological data show that ash beds were correlated to heavy rainfall in 2000, 2001 and 2002 which years occur volcanic ash fall at mountain, and a thick sandy mud bed was corresponded to strong typhoon events in 2004 to 2005. Heavy rainfall supplies ash material to bottom of seafloor from rhyolite volcano Iwo-Dake depositing unformed tuff-rich sediment which was deposited at the top of volcano during. Strong typhoon drives Al and Si-bearing material to Nagahama Bay and these materials are re-sediment together as sandy mud bed. We will try to identify iron formation mechanism to identified relationship between hydrothermal activity and sedimentation. Before estimation of iron formation, at least we subtract wave and rain effects. Unformed iron-oxyhydroxides mud accumulated rapid speed at 33.3 cm par year at 1m-sediment-trap cores placed on the seafloor. From meteorological comparison dating, estimated accumulation rate of iron-oxyhydroxides mud is 4.7 cm par year. As a result, we estimate that approximate 800 cubic centimeter iron-oxyhydroxides discharge from bottom of seafloor, and only 14 percent preserved in this Nagahama Bay.

The stratigraphy of Pliocene to middle Pleistocene pyroclastic deposits, Miyagi Prefecture, Japan

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In the Kurikoma geothermal area on the frontal zone of the Northeast Japan arc, a caldera cluster has been formed during recent 9Ma, through the repeated explosive volcanisms which numerous tephra layers in the east of the cluster. Among the tephra, the latest 4 pyroclastic flow layer; Ikeduki, Shimoyamazato, Nizaka, Yanagisawa tuff layers have been well determined their localities of vents along with their eruption ages ranging from 0.3 to 0.04Ma. However, the tephra layers preceding to the above 4layers have not been well defined in terms of their lithostratigraphy, eruption ages, or localities of eruption vents. These have been regarded as the members of the Pliocene to middle Pleistocene Onoda Formation. We reported the stratigraphy of the eruptive product in the Onoda Formation: Takatama (3.3±0.3Ma), Shimatai, Yubama, Chijimisawa (1.00±0.06Ma), Mozume (1.08±0.13Ma and 0.62±0.10Ma), Toshojisawa (0.87±0.21Ma), and Uguisuzawa pyroclastic flow deposits in stratigraphic order with Aonosawa tephra layers at the top (Kuzumaki and Ohba, 2010, 2011).

In this study, the stratigraphy of pyroclastic deposits in Onoda Formation are reexamined on basis of newly identified deposits, and the frequency of pyroclastic eruption are examined.

At the 4 newly discovered localities (St, Ot, Tt, and Kt) 7, 5, 3, 2, distinct tephra layers are identified. The layers Kt-1 and -2 and Tt-1, -2, and, -3, in are to be stratigraphically lower than the Yubama pyroclastic flow deposit, because Kt-1 and -2 are overlain by Yubama pyroclastic flow deposit, and the topography of deposition for Tt-1, -2, and, -3 is lower than Kt-2. Since St-7 is correlated petrologically with Mozume pyroclastic flow deposit, six pyroclastic deposits, St-1~-6, are stratigraphically higher than Mozume pyroclastic flow deposit.

At least seventeen distinct pyroclastic deposits above the Chijimisawa pyroclastic flow deposit of ca. 1.0Ma are identifiable in this area. Therefore, the frequency of pyroclastic eruption is higher than 1 in every 0.06Ma.

Volcanic history of the Takahara Volcano, Northeast Japan arc: Inference of the caldera activity

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Introduction

Caldera activity has large effect on environmental and geomorphic change. Therefore, clarification of the volcanic history and evolution of magmatic processes is necessary for a long-term prediction.

In Southern part of the Northeast Japan arc, which is south than Fukushima, most of the caldera activity is before Calabrian, and they are not remarkable expect Takahara volcano after Middle Pleistocene.

Takahara volcano currently formed in northern Kanto plain about 140 kilometers away from the Tokyo, and the Shiobara caldera about 7 kilometers in diameter existence in northern foot of Takahara volcano, which formed at 0.3Ma in former research. Then, large andesitic stratovolcano with an altitude of nearly 2,000 meters formed after 0.2-0.3Ma. A part of caldera is filled with the lava from stratovolcano. The central part of stratovolcano eroded very much, it is suggest that there is no eruption from summit recently. By contrast, a dacitic central cone formed in the Shiobara caldera at Holocene and fumarolic activities around central corn are still continuing. Thus, the two types volcanism recognized in Takahara volcano. However, the volcanic history is not clarification because there is only insufficient informational about stratigraphy and radiometric age.

The purpose of this study, therefore, to clarify volcanic history and evolution of magmatic system of Takahara volcano based on the whole rock chemical analysis and radiometric age determination of Takahara volcanic rocks.

Results

In the pre-caldera stage (<0.6Ma) of Takahara volcano, tholeiitc basalt to andesite volcano was mainly formed with multiple magmatic systems.

In the caldera forming stage (0.6-0.3Ma), The marker tephra and radiometric age of ignimbrites from Takahara volcano indicated that several ignimbrites erupted in 0.6Ma and 0.3Ma which is a formation factor of Shiobara caldera. When the caldera formed for the first time about 0.6Ma, the two ignimbrites erupted from multiple magma chambers has different chemical composition, which are called Kanawazaki PFD and Katamata PFD. These ignimbrites widely covered the Nasunogahara region in northern Kanto plain.

After that, basalt to rhyolite lava flows erupted from tholeiitic magma chamber. At the second time of the caldera formation, Tanohara PFD erupted about 0.3Ma. Then, the magmatic system extremely changed at post caldera stage (>0.3Ma), and andesitic to dacitic stratovolcano built by newly supplied calc-alkaline magma. The eruption style of stratovolcano is non-explosive because it is composed mainly of lava flows and intercalated with small-scale scoria beds.

The center corn erupted at the Holocene is characterized by biotite. It was not contained in volcanic rocks of post-caldera stage indicates that the high water content magma recently is supplied.

These results infer that the difference in eruption styles was caused by complex magmatic systems in Takahara volcano.

Post and pre caldera eruption history of Miyakejima Volcano - Entombment process of Hachodaira Caldera and eruption history of pre A.D. 2000 Caldera -

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Collapse caldera is a common volcanic structure in basaltic volcanoes. However, the entombment process of the caldera and the eruption history of the post-caldera are poorly understood. To make an effective forecasting of the volcanic activity, we have to understanding the variations of the eruption activities during the caldera filling stage based on the eruption history of the post-caldera period of many volcanoes. Based on the caldera wall observation, tephrochronology, and radiocarbon dating, in the Miyakejima Volcano, we clarify the entombment process of Hachodaira Caldera and the eruption history of the pre A.D. 2000 Caldera.

The cross section of Hatchodaira Caldera, forming age at ca. 2.5 ka, is exposed on the wall of the A.D. 2000 caldera on Miyakejima volcano. The cross section of Hatchodaira Caldera is divided into 7 units; pyroclastic cone (130 m thick), many thick lava flows (200 m thick), single lava flow (5-10 m thick), scoria fall deposit (40 m thick), lava flows (30 m thick) and scoria fall deposit, in ascending order. The caldera was filled mainly by the lava flow which makes a lava lake. On the other hand, many large-scale fissure eruptions, such as Kazahaya Scoria at 1.4 ka (ca. the 6th century, radiocarbon ages calibrated to calendar years) occurred outside of caldera during the caldera-fill stage (ca. 2.5 ka to the 9th century) of Hatchodaira Caldera. The production rate during the caldera-fill stage of Hatchodaira Caldera is estimated at least 0.4 km^3 / ky. This value is larger than the production rate 0.2 km^3 / ky for the last 1100 years after the caldera filling stage.

After the 9th century, the eruption number of pre-A.D.2000 Caldera is 17 times. These eruptions are flank fissure eruption in most cases. The frequency of eruption is 1-2 times in 100 years. Just before the formation of the A.D. 2000 Caldera, the frequency of eruption was slightly larger (3 times in 100years). But it is not a significant difference.

Were the Pre Lower Pumice 1, Lower Pumice 1 and Lower Pumice 2 eruption sequences sourced from the same magma reservoir, Santorini Caldera, Greece?

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The Santorini Archipelago of Greece preserves 650 kyr of volcanic activity, including 12 major explosive eruptions, which incorporate two 180 kyr mafic to silicic magmatic cycles, as well as the remnants of multiple lava-dome complexes, lava shields, stratovolcanoes and at least four caldera collapse events. The 3.5 ka Minoan eruption terminated the second magmatic cycle and was responsible for the destruction of a Minoan settlement at Santorini. The Pre Lower Pumice 1, Lower Pumice 1 (183.5 ka) and the Lower Pumice 2 (172 ka) eruptions ended the first magmatic cycle and are considered chemically similar to deposits of the Minoan eruption (dates from Keller et al. 2000). This could suggest cyclicity in magma generation processes.

The Pre Lower Pumice 1, Lower Pumice 1 and Lower Pumice 2 eruption deposits are variably exposed within the caldera cliffs and outer extremities of southern and eastern Thera. The Pre Lower Pumice 1 sequence is represented by 13 small volume pyroclastic fallout, ignimbrites and obsidian clast surge deposits, the latter resulting from the volcanic destruction of a lava dome. A paleosoil separates the Pre Lower Pumice 1 succession from the overlying pyroclastic fallout (LP1-A), ignimbrite (LP1-B) and lithic-rich lag breccia (LP1-C) deposits of the Lower Pumice 1 eruption. The Lower Pumice 1 eruption sequence is disconformably overlain by pyroclastic fallout (LP2-A), ignimbrites (LP2-B), phreatomagmatic ignimbrites with basal layer 1 ground breccias (LP2-C), and lithic-rich lag breccia (LP2-D) deposits of the Lower Pumice 2 eruption.

Crystal-poor, dacitic white pumice fragments represent the dominant juvenile product within each sequence. Subordinate abundances of transitional basaltic-dacitic banded and grey pumice fragments, in addition to mafic scoria, are also present. Chemically, these rock types depict two magma batches: (1) a dacitic (to rhyolitic) magma, and (2) a basaltic magma. The intrusion and subsequent mixing and mingling of the mafic magma with a cooling dacitic-rhyolitic magma, is considered responsible for the formation of both banded and grey pumice fragments within each eruption sequence. C1 chondrite normalised rare earth element (REE) plots, of dacitic white pumice fragments, depict uniformity in REE patterns within and between eruption sequences. This suggests an homogeneous source for each eruption and indicates the presence of a long lived magma reservoir. Episodic basalt magma injection into this reservoir may have triggered each eruption.

Long-term volcanism around active calderas in Bali and Tengger-Bromo region, East Java, Sunda arc

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We study the long-term volcanism around the active calderas in Bali and Tengger-Bromo region, East Java. Mass fractionation correction method is utilised for the mass spectrometry of K-Ar dating, which accounts for the fractionation of initial argon ratios. Lava samples having pilotaxitic or intergranular groundmass texture are selected for dating in order to obtain accurate and precise ages. Some of the samples dated are estimated to contain initial argon ratios that are fractionated from atmospheric values.

We have identified three active periods of volcanism in Bali. They are 1.6-1.5 m.y. BP, 0.7-0.5 m.y. BP, and 0.2 m.y. BP to present. Volcanic rocks to the west of Bratan caldera were formed by the 1.6-1.5Ma activity. Volcanoes consisting the northern aprons of caldera sommas were formed by the 0.7-0.5 Ma activity. Between 0.2-0.1 Ma, volcanism occured extensively around present Batur and Bratan calderas. The shield volcanoes consisting the somma of Batur and Bratan have started to form by covering the 0.5 Ma volcanoes. Batukau, EL 706m volcano near Pasek, and Cemara volcanoes were also formed in this period. From 0.1Ma to present, the activity continued at Batur somma and formed Abang peak. Agung volcano started to form by 0.05 m.y. BP. Both Batur and Bratan systems have produced caldera-forming eruptions multiple times in the past 0.03 m.y., and their intra-caldera activity has continued along with the activity of Agung.

Caldera-forming eruptions of Tengger-Bromo system are older than Bali calderas, yet the volcano is still very much active. The two calderas are Ngadisari and Sand Sea. The activity of Tengger volcano started with the formation of northern somma (Pananjakan) in 0.5-0.45 Ma, after the 1.2 m.y. hiatus following the formation of 1.7 Ma Kukusan volcano. The aprons were formed in the subsequent active periods. More than half of the edifice volume erupted between 0.35-0.2 Ma and have formed much of the aprons, with average eruption rate greater than 2km3/ky. The northeastern to southern somma, and the northern apron, were formed in 0.35-0.3 Ma. The eastern apron and the southwestern apron were formed in 0.25-0.2 Ma. Lavas and cones in the northwestern apron, and Ngadas basalt and andesite lavas (which fill the Ngadisari caldera), have formed in 0.08-0.06 Ma. The age of Sand Sea eruption is determined to be about 0.05 Ma from stratigraphy relations. Therefore, the central cones are found to be younger than 0.05 Ma, which is consistent to 14C ages of tephra at the caldera rim from previous study. The average eruption rate of the central cone activity is calculated to be about 0.1 km3/ky. Petrography and whole-rock chemistry of ejecta from the central cones, including the active vent (Bromo), are similar to those of Ngadas lavas and Sand Sea eruption PDC deposits. These observations imply that the present magma supply and accumulation system is similar to the one prior to the Sand Sea eruption.

Vent migration and caldera collapse during the Minoan eruption of Santorini

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The late 17th century BC Minoan eruption of Santorini discharged 30-60 km3 of rhyodacitic magma, and minor andesitic magma, and collapse deepened and widened a partially flooded 21 ka caldera already present in the northern half of the volcanic field. The resulting present-day caldera has distinct northern and southern basins, separated by a NE-SW line of tectonic weakness (Kameni Line, KL). Juvenile and accidental component populations from the deposits exhibit systematic variations between the four eruptive phases, allowing reconstruction of vent migration during eruption. The plinian phase (phase 1) discharged rhyodacite and a suite of compositionally distinctive Ba-rich andesites from a subaerial vent situated on the KL. The vent then migrated northwards into the ancient caldera, causing eruption of syn-plinian base surges (phase 2) then cohesive, low-temperature pyroclastic flows (phase 3). The andesitic magma ceased to be erupted as the vent migrated away from the KL. However, the phase 3 tuffs contain abundant black, glassy andesitic lithics that are chemically very similar to the juvenile Ba-rich andesite, and which are pieces of a partly subaqueous lava complex present in the 21 ka caldera prior to the Minoan eruption. Blocks of lava compositionally identical to Minoan rhyodacite were also discharged in abundance during phase 3. The lithic assemblage is uniform throughout phase 3, suggesting a single vent situated within the 21 ka caldera, consistent with Pfeiffers (2001) ballistic data. Phase 4 discharged hot pyroclastic flows that poured into the sea forming three ignimbrite fans (NW, E and S). The first flows (phase 4a) were erupted from one or more vents in the north and laid down lithic-block-rich ignimbrites and lag breccias containing abundant clasts of Tertiary basement. These constitute much of the NW ignimbrite fan, and contain gas escape pipes suggesting that some of the lithic debris was wet when incorporated into the flows. Subsequent flows (phase 4b) were much poorer in block-sized lithics and laid down the hot, fine-grained, tan-coloured ignimbrite typical of phase 4. Package 4b, which accounts for most of the onland ignimbrite, contains only trace amounts of basement clasts, makes up the S and E ignimbrite fans, and overlies package 4a in the NW. The greater thickness of the S and E fans compared to the NW fan suggests that, unlike phase 4a, the phase 4b flows were erupted from the area of the present-day southern basin. Moreover, their hot, dry nature shows that that the erupting vents were subaerial, being sited south of the flooded 21 ka caldera. In summary, the principal eruptive vents migrated from the KL first northwards into the ancient flooded caldera (future northern basin), then southwards onto dry land (future southern basin). Caldera collapse in the north may have begun as early as phase 3, but the southern half of the caldera was still subaerial when the eruption ceased.

The 2008 eruption of Okmok volcano, Alaska: Ascent of magma into shallow intracaldera groundwater system and resulting ephemeral landforms

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Okmok volcano, a young, largely basaltic andesite caldera system in the Aleutian Islands of Alaska, erupted explosively over a 5 week period between July 12 and August 23, 2008. The eruption was predominantly phreatomagmatic, ultimately generating an estimated 0.4 km3 (bulk volume) of tephra that covered much of northeastern Umnak Island. Eruption onset was abrupt and explosive, producing a tephra column that reached 16 km above sea level in the first four hours. Subsequently, tephra emission was of variable but much lower intensity through the eruption's end. Okmok is remote and the eruption was poorly constrained by eyewitness observations. Four synthetic aperture radar images taken during the eruption, combined with post-eruption fieldwork and analysis of photography, record a complex sequence and evolution of explosion and collapse craters, and development of a several hundred meter high tuff cone.

The eruption began as ascending magma encountered shallow groundwater beneath the caldera floor, prompting multiple explosions along a crudely arcuate zone about 2 km long. At least six overlapping, 100 to 300 m diameter craters formed within, and adjacent to, a larger crater that had destroyed part of a prominent post-caldera cone. Continued venting promoted coalescence of the new craters and by day 12 only four distinct, larger craters were visible. Two of these in the center of the 2 km long zone ultimately formed distinct positive relief features (tephra cones) that served as primary vents for much of the eruption. Craters at each end of this zone appear to have hosted sporadic explosions but were not sites of continuous ash emission. These marginal craters grew further in size through the eruption by additional explosions and collapse. Both filled with water during and after the eruption. Vigorous post-eruption erosion and deposition are rapidly altering these craters and will likely, within a very short time, render them unrecognizable as part of the initial 2008 vent system. Similarly, several dozen 10 to 200 m wide collapse craters that formed north of the primary eruptive vents prominent in the weeks following the eruption were quickly degraded beyond recognition. The strong involvement of water, complex explosion histories, and rapid reworking that occurs during protracted phreatomagmatic eruptions may frequently obscure details of initial vent geometry. Documentation of this process during the 2008 eruption of Okmok volcano, Alaska, serves as a cautionary note for interpreting older phreatomagmatic deposits and landforms.

Linking lava domes to their structural setting

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The eruption of lava domes can be strongly controlled by local and regional structure, yet it is not always easy to observe this volcano-tectonic relationship. We infer that the conduits for these eruptions will often be close to, or along, major faults and so the internal structure of the dome, defined by the shape and position of the conduit, can also be linked to the structural setting. To investigate the volcano-tectonic relationship, we have focussed our studies on the internal structures of lava domes that sit within two different calderas in the Taupo Volcanic Zone (TVZ) of New Zealand. At Ngongotaha Dome, Rotorua Caldera, quarrying has exposed a cross section through part of the dome, and at Tarawera Volcano, Okataina Caldera Complex, a rift produced during the historical 1886AD eruption exposed part of the interior of the domes. In such a hyperactive caldera-forming region like the TVZ, it can be difficult to observe the geometry or structure of calderas because of their rapid burial, and thus, domes may remain as their only structural clue.

At Ngongotaha Dome, a fan-like arrangement of flow bands from the outer edge to the centre suggests a central dyke-fed conduit running parallel to the outer edge of the dome. The location and morphology of the conduit can be related to caldera structures, as flow band orientations from within the dome matches elongation of gravity lows associated with caldera collapse. Post dome growth fractures share similar orientations to the dominant northeast trending structural grain of the region. We compare the structural orientations within Rotorua Caldera (gained from mapping of Ngongotaha Dome) to those at nearby Okataina Caldera Complex, in order to investigate the volcano-tectonic evolution of the regional structure.

Tarawera Volcano is more complex. Previous research has concluded that the domes of Tarawera were inflated with minor flow development, as suggested by the presence of an onion skin-like circular flow band pattern. However, flow bands are often near vertical above the proposed conduit, and show a wide variety of orientations at the flanks of the dome. Instead, a series of vertically emplaced sheets that were then carried outwards from the vent is suggested as a possible method of emplacement of this dome.

Analysis of the internal structures of lava domes can provide a wealth of knowledge as to the emplacement of the dome and structural setting it resides within. In particular, where other structural clues like faults are missing, internal structures and morphologies of lava domes can help to reproduce structural maps at a caldera scale. These structural maps can also provide insights into the wider regional scale tectonics and evolution of the structure of the TVZ.

Petrology and geochemistry of the 2011 eruption of Nabro, Eritrea

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Nabro volcano in Eritrea is a large caldera system that forms a lineament between the Red Sea and the main Afar spreading system. The largest recorded historical eruption in Africa took place at its neighbour, Dubbi, in 1861 (Wiart and Oppenheimer, 2000). Nabro erupted in 2011, producing a trachy-basaltic lava flow that travelled 15km along the Ethiopia-Eritrea border, displacing communities and generating the largest SO2 emission since Pinatubo (Bourassa et al., 2012). Older deposits around Nabro range from trachybasalt to rhyolite in composition, following a mildly alkaline trend with LREE-enrichment. There is a very large ignimbrite deposit, possibly associated with caldera formation, around much of the volcano, demonstrating its range of potential impacts. We present new geochemical and petrological data from the eruption, including whole-rock and mineralogical data. Preliminary results from experimental studies of the 2011 products will be discussed. These studies provide insights into tectonic processes in the Afar region and its dynamic evolution, as well as the potential hazards from future eruptions of a complex caldera system.

Probable time correlation between the eruption of Baitoushan volcano and the megathrust earthquakes in Japan

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From 2002, Baitoushan volcano revealed the sign of magma activity such as the increase in seismicity and upheaval of the summit. This activity ceased in 2005. After six years from this sign, the 2011 Tohoku earthquake occurred in Japan. This gave an anxiety of the eruption of Baitoushan volcano as in the case of active volcanoes in Japan. There is a historical basis in this anxiety like as in 9th century history in East Asia including Japan and the Asian continent.

To examine the possibility of the Baitoushan eruption, we need the knowledge of historical correlation between the eruption and megathrust earthquakes in Japan. We have many precise historical records on the megathrust earthquakes in Japan, contrary to this, we have poor knowledge on the ages of Baitoushan eruption. In this study, we identified the eruption ages of Baitoushan volcano carefully based on the analysis of old documents. They were compared with the ages of megathrust earthquakes in Japan.

The eruption age adopted for consideration is following five ages. June 24 1373, October 7-9 1597, June 9 1702, 1898 and 1903. In addition to these ages ca.940 is adopted as the millennium eruption age based on the wiggle matching dating and the analysis of history of turmoil in Northeast Japan. Although some papers adopted 1403, 1413, 1668, 1900 and 1925 as the eruption age, I did not adopt them because of no description in primary document or doubt of yellow sand.

Among these eruption ages (6 data), the age interval was 5 to 433 years, and was an average of 193 years. Total age interval with 3sigma (standard deviation) accuracy was as large as 860 years within the examination period covered for 1070 years after ca.940. Thus it was meaningless to assume a periodicity. On the other hand, the age difference (tB-tJ) between the eruption (tB) and the maximum proximity megathrust earthquake (tJ) [4 data sets; reliable data relatively] ranged from -8 to +12 years, and it was an average of +1.3 years. Within the examination period covered for 640 years from 1373 with document record to the present, the total age difference with 3sigma accuracy was only 43 years, enough small to assume the correlation between the eruption and the megathrust earthquake.

Then, does an eruption occur after the megathrust earthquake of 3.11 in Baitoushan volcano? Supposing it erupts, when does it occur? There are some facts related on this problem; historical correlation between the Baitoushan eruption and the megathrust earthquakes along the Japan Trench, recent magma accumulation, and the stress field change after 3.11 from compressional to extensional. All these facts indicate the possibility of eruption of the near future. If it will occur in relation to the 3.11 megathrust earthquake, the age will be by 2034 with 3sigma accuracy.

The Mt. Paektu Geoscientific Experiment

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Mt. Paektu/Changbaishan volcano is an enigmatic volcano straddling the China — DPRK border. Its most striking features are the ~5.5–km–wide crater at its summit, and the magnificent lake it hosts. The crater was formed during one of the largest known historical eruptions, which took place around the middle of the 10th century CE. The so-called “millennium eruption” resulted in significant tephra fallout as far as northern Japan, highlighting the potential long-range impacts of volcanism on this scale. Since this event, three smaller eruptions have been documented, the most recent of which occurred in 1903. More recently, in 2002–2005, elevated levels of seismicity were recorded beneath the volcano. This has led to increased surveillance and geological work aimed at identifying the structure of the volcano, and revealing further details of the nature of the “millennium eruption”. We will describe a joint UK/US/DPRK project engaged in study of the Korean side of Mt. Paektu/Changbaishan. We plan to deploy a linear array of six broadband seismic stations for one year. Primarily using the receiver function technique, we will image major crustal discontinuities and attempt to reveal where melt may be ponding in the crust. Further, we plan to perform audio-frequency magnetotelluric soundings to determine the conductivity of the crust along the same profile. By highlighting regions of high conductivity and low seismic velocity we will thus show regions of melt storage beneath the volcano. Additionally, we will investigate both seismic and electrical anisotropy, in order to infer the geometry of any magma bodies. We will also carry out new work to quantify the nature and impacts of the “millennium eruption”: this will include experimental studies to determine pre-eruptive conditions, and deposit characterisation (isopach and isopleth mapping and modelling based on an improved dataset with new borehole data) for modelling eruptive processes/dynamics. We will also investigate the record of eruptions that have taken place both prior to and since the “millennium eruption”. We expect to carry out fieldwork in the summer of 2013, following the meeting in Kagoshima and also in summer 2014. This contribution will therefore focus on reporting on the goals and planning for this international project.

Formation of Qixiangzhan Eruption of Changbaishan Tianchi Volcano, China

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To comprehensively understand the eruption characteristics and history of active volcano is crucial for predicting its future eruptions and hazard. Changbaishan Tianchi Volcano (CHTV) is one of the most dangerous active volcanoes in Northeast Asia. It had experienced three periods of large-scale eruptions since the Holocene, i.e. the Tianwenfeng period at about 5,000 years ago, the Qixiangzhan (QXZ) period at about 4,000 years ago and the Millennium eruption at about 1,100 years ago, respectively. The type of Tianwenfeng and Millennium eruptions is commonly accepted to be a typical Plinian eruption. However, there arises a considerable debate about the type of QXZ eruption as to whether it is effusive or explosive. In high-resolution remote-sensing images, the morphology of the products of QXZ eruption looks like a lava flow, which flows along the northern slope of the volcanic cone about 5.4 km in length and 400-800 m in width. However, the recent research work by the author has revealed that the QXZ eruption should be a small-scale pulsed explosive eruption. The main evidence is as follows: 1) The bulk-rock composition of QXZ eruption products is characterized by high SiO_2>71% and Na_2O+K_2O >10% contents representative of alkaline magma, which has high viscosity, low flowing ability and extremely high potential of explosive eruption; 2) Field observations show that the QXZ eruption products appear as thin layers about 2-5cm in thickness, significantly different from the massive or slaggy structures of lava flow; 3) Microscopic observation reveals that most of the phenocrysts in the QXZ eruption products were severely broken by explosion to form angular grains with well developed micro-cracks. The vesicles in the QXZ eruption products are irregular in shape and have rough margin, different significantly from the elliptical and smooth margin vesicles commonly observed in lava flow; 4) Stereomicroscopic observation shows that the QXZ eruption products are composed of clastic particles and exhibit grain-supported texture with well developed irregular vesicles. Further study by using SEM indicates that most of the clastic particles are fine volcanic ash and tiny pumice with rough surfaces. Basing on the above analyses, we may conclude that the QXZ eruption can be assigned to a small-scale pulsed explosive eruption. During the explosive eruption, a large number of fine pyroclastic particles flowed down the mountain slope as a high speed pyroclasstic flow to form thin layer of ignimbrite. Over many times of explosive eruptions, layer upon layer of ignimbrite were accumulated, resulting in a shape just like lava flow. Therefore, all the three large eruptions of CHTV in Holocene can be assigned to explosive eruption, rather than the previously proposed model of explosive-effusive-explosive explosions.

Textural characteristics of the Holocene pumice erupted from Changbaishan volcano and their volcanological implications

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The texture of volcanic products records abundant information about the physical and chemical processes of the magma. Therefore, the quantitative analysis of the texture of volcanic products has recently become an important research method in volcanology. Changbaishan volcano located on the border between China and North Korea, is one of the largest active volcanoes in China. It has experienced at least five explosive eruptions in the Holocene, i.e. 5,000 BP eruption, AD 946 eruption (also called "millennium eruption"), AD 1668 eruption, AD 1702 eruption and AD 1903 eruption. In this study, the composition and quantitative texture of pumices from three explosive eruptions in Holocene (5000 BP eruption, the millennium eruption and AD 1668 eruption) of Changbaishan volcano were studied in detail. The results show that, the pumices from 5000 BP eruption and the millennium eruption are all pantellerite in composition, but the later is more acid than the former. The pumices from 1668 AD eruption are high potassium trachyte in composition. The pumices from these three eruptions comprise mainly vesicle of different sizes, vesicle wall and a small amount of phenocrysts (<15%). The parameters of vesicles are extracted from back scattering SEM images with different magnifications. The pumice from 5000 BP eruption has the highest vesicularity (about 73.4%), the smallest size (about 1 um) and the greatest number density ($4.23 * 10^{16}$ m $^{-3}$) of vesicles. The pumice from the millennium eruption has the vesicularity of 62.8%. The smallest vesicles in this pumice are several micrometers in size, and the number density is $3.25 * 10^{15}$ m $^{-3}$. The pumice from AD 1668 eruption has the vesicularity of only 45.9%, the vesicles are generally larger than 10 um in size, and the largest may reach up to 1 cm. In pumices of this period, the number density of vesicles ($3.68 * 10^{14}$ m $^{-3}$) decreases and the vesicle walls become thicker. Finally, according to the compositions and number density of vesicles in pumices from three eruption periods, we have estimated some important physical parameters, such as the decompression rates, height of eruption column and magma discharge rate for these three eruptions. The results from this study may provide important scientific basis for understanding magma process and determining the intensity of historical eruptions of Changbaishan volcano.

Characteristics of Pyroclastic-flow Facies in Millennium Eruptionin of Tianchi Volcano,Changbai Mountains,China

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Tianchi volcano is the largest composite volcano in China, which is at the boundary between China and North Korea. In 946±3, there was a large plinian eruption in Tianchi volcano which is called millennium eruption. Millennium eruption produced widespread pyroclastic-flow deposits.

This paper has studied thestrata, litho, geochemistry, grain-size and transportation of ground-surge from pyroclastic-flow of millennium eruption in Tianchi volcano. The main conclusions which have been got are as follows:

(1) The proximal strata of pyroclastic-flow are combined with the eutaxite structures and lava-like structures. The median strata are combined with massive beds, pumice-rich layers, litchis-richer layers and welded zones which are representative of the transportation processes for gravitational differentiation. And columnar joints and block structures are also developed which are representative of the deposition processes for cooling. The distal strata are combined with coarse-tail beds, ground surge beds and climbing beds. There are also some altered beds because of flood. The distal pyroclastic-flow strata have some fluidized characteristics.

(2) The proximal ignimbrite is alkaline trachytic welded tuff. The median ignimbrite is also alkaline trachytic welded tuff. And the distal ignimbrite is alkaline rhyolite. The welded tuff is weaker from the proximal to the distal.

(3) The proximal and median black pumice is trachyte. And the distal gray pumice is rhyolite.

(4) The median diameters of pumice which is less than 64mm from the median and distal strata have an increasing tendency with the distance increasing from the crater. And the median diameters become smaller with the depth increasing from the top of strata. The Sphericity (Spht) has an increasing tendency with the distance increasing from the crater. And the contents of lithoclasts in number percentage decrease with the distance increasing from the crater which reveals gravitational differentiation.

(5) With the pumice becoming smaller, there are more angles, richer irregular shapes and simpler transportation. The grain-size distributions of fine ashes are similar and have a single peak which is close to the fines.

(6)The histograms of ashes cloud and ground surge have a similar characteristic which is ladder-like and close to the fines. And the histograms of pyroclastic-flow have many peaks which are representative of the composite transportation.

(7) There was hydration at the distal part of pyroclastic-flow, and the ground surge came from pyroclastic-flow and water interaction in Baixi.

History of Volcanic Activity, Magma Evolution and Eruptive Mechanisms of the Changbaishan Volcanic Province

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Three giant stratovolcano near the border of Sino-DPRK , including Nanbaotai volcano (2343 meters in altitude), Wangtiane volcano (2051 meters in altitude) and Tianchi volcano (2749 meters in altitude), record the migration path of volcanism in this area. All the volcanoes endured shield-forming and cone-forming stages. Wangtian'e volcano began to erupt in Pliocene and fall into silence in the early Pleistocene (4.77 Ma-2.12 Ma) (Fan et al.,1998). Tianchi volcano endured three eruption stages: potassium trachybasalt shield-forming stage in the early Pleistocene (2.77-1.203Ma), trachyte cone-forming stage in the middle and late Pleistocene (1.12-0.04Ma) and violent eruption of pantellerite in the Holocene (Fan et al., 2006, 2007).

The history record has implied many eruptions in the Changbaishan area in the Holocene time, whereas it is still hard to identify whether the exact eruption spot is in Tianchi volcano. Although scholars reach an accord on the Millennium eruption events in Tianchi volcano, the vague history records and the decoupled geological dating data are still under debating. On the south and north slope of Tianchi volcano, white pantellerite pumice are covered by black melted trachyte pyroclastic rocks, indicating a medium eruption has happened after the Millennium eruption events. Studies on major and trace elements and isotope geochemistry show that the Changbaishan volcanoes have a similar trachybasaltic magma system with its primary magma of potassic trachybasalt nature. The composition of the magma experienced a evolution from basaltic to trachytic to pantellerite (Fan et al., 2006, 2007).

The studies suggest that there are crustal magma chamber and mantle magma chamber under the Tianchi volcano. The two chambers interact with each other and cause batch eruption (Fan et al., 2007). Since the mantle chamber continually supplied trachybaslt influx from below to the crsutal chamber, the Tianchi Volcano is a long-life volcano. Fractional crystallization and magma mixing were two important processes in the Tianchi Volcano-the former determined the bimodal characteristics of the volcanic rocks, and the latter triggered the volcanic eruption. Additionally, some mantle sourced magma of potassic trachybasalt compostions erupted directly to the surface and resulted in widespread isolated small cinder cones around the Tianchi volcano.

Subduction of the western Pacific plate and the subsequent back-arc extension of NE Asia dominate the mechanism of the Changbaishan Volcano.

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ORIGIN OF CENOZOIC BASALTIC LAVAS IN THE ERDAOBAIHE RIVER VALLY, CHANGBAISHAN, CHINA

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The Tianchi volcano in the Changbaishan on the border between China and North Korea is composed of the Pliocene to early Pleistocene basaltic shield, middle to late Pleistocene trachytic composite cone. It is an active volcano because of several eruptions in the Holocene.

In this study, we surveyed basaltic lava sections in the Erdaobaihe river valley and analyzed chemical composition of the lavas. They consist of basalt in upper level and trachybasalt and basaltic trachyandesite in middle to lower levels. The lavas are similar in REE patterns, suggesting that they likely share the same source. In the diagram of Na_2O-K_2O and La-La/Yb,basalts are shown as Na-rich and tholeiite series, whereas, trachybasalt and basaltic trachyandesite are K-rich and alkali-series.Their $Mg^{\#}(=100Mg^{2+}/(Mg^{2+}+Fe^{2+})<60)$ are lower than that (=60-68) of Cenozoic primary basalt magmas in the eastern China. Their K/Rb ratios (0.05-23.15) and Ni contents (27.76-200.61) are less than primary mantle, whereas Ba/Rb ratios(15.64-264) are greater than primary mantle. All lines of evidence indicate that these lavas originate from evolved magma. The SI values for basalt and trachybasalt are less than 40, and SI values for basaltic trachyandesite are in the range of 20−29. The lavas contain phenocryst of olivine, pyroxene and plagioclase. There are positive anomaly of Ba in trace element pattern and negative anomaly of Eu in REE pattern. These geochemical features reveal that tholeiite formed from mantle derived magma which underwent crystal fractionation. Higher K_2O (>2.0%) of trachybasalt and basaltic trachyandesite indicate that variable degrees of contamination may occur during magmas ascending. The discrimination diagrams of Zr-Nb-Y and Zr/Y-Zr show that the lavas formed in inner plate setting.

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Volcanic geology, geochronology and geochemistry information provided by the Halaha River and Chaoer River volcanic field in Daxing'an Mountain Range

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34 Quaternary volcanoes, which scattered along a Quaternary NE strike fault, are found in the area of Halaha River and Chaoer River, middle of Daxing'an Mountain Range. Quaternary volcanic rocks in this area, mainly alkaline basalt, cover an area of ca. 400 km^2. Both magmatic eruptions and phreatomagmatic eruptions are found in this area. The magmatic eruptions form a series of products, including scoria cones, tephra fallout deposits, and many kinds of lava (e.g. aa lava, pahoehoe lava and block lava). Typical fumarolic cones and lava hillocks are found in the lava. The phreatomagmatic eruptions have typical base surge deposits, which are characterized by parallel bedding and staggered bedding. Volcanic activity in this area form many volcanogenic lakes. According to the difference of lake forming, they are divided into four types: crater lake, maar lake, volcanic dammed lake, collapse lava lake (Zhao et al., 2008).

Based on studies on the volcanic field characteristics, in conjunction with geological dating by K-Ar, it is identified that the volcanism occurred in four periods: Early Pleistocene, Middle Pleistocene, Late Pleistocene and Holocene. Basalts of Early Pleistocene, mostly mantled by the later volcanic rocks, are distributed in the margin and valleys of the volcanic field. Middle Pleistocene, the most volcanic active period in this area, witnessed the formation of more than half of Quaternary volcanoes and lava spreading. Moderate volcanism occurred in Late Pleistocene which produced a small amount of volcanic deposits. Volcanic activities are strengthened again in Holocene Period, characterized by strongly explosive explosion, widespread lava flow and well-keeping lava landforms features (Fan et al., 2011).

The volcanic rocks, dominated by alkali olivine basalts in sodium series, is characterized by relative enrichment in large ion lithophile elements and light rare earth elements. The fractionation of rare earth element of the basalts is weak($(La/Yb)_N$ =8-12).They resemble alkali basalts in Datong, as shown by trace elements distribution patterns, and generally exhibit OIB-like characteristics. The basalts show nearly homogeneous Sr-Nd-Pb isotopic composition similar to MORB source and present depleted mantle characteristics. All data show that basalts of HC have a garnet lherzolite mantle source, low degree partial melting(8%-15%)in which results in the primitive magma. Crystal fractionation of olivine and pyroxene from the magma is weak and seldom contamination by the crust rocks happens during the magma ascending, which resulting the volcanic rocks with high MgO content(>9wt%), Ni content and Mg value(60-70).Regional extension triggers asthenospheric upwelling, which may lead to the genesis of magma and subsequent volcanism (Zhao and Fan, 2012).

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Origin of Cenozoic basaltic magmatism at Changbaishan volcanic field, northeast China

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In NE China, Cenozoic intraplate basalts are widely distributed, and Changbaishan is one of the largest volcanic fields. This intraplate magmatism is unique because the stagnant slab of the subducted Pacific plate is present in the mantle transition zone (MTZ). Therefore, the geodynamic and geochemical processes in relation to the stagnant slab and their effects on the magmatism have received considerable attention (e.g., Zou et al., 2008; Ohtani and Zhao, 2009). This paper summarizes the results of our recent studies on the Cenozoic basalts in NE China (Kuritani et al., 2009, 2011, 2013), and integrates them toward understanding the origin of the basaltic magmatism at Changbaishan.

A prominent low-velocity anomaly with a plume-like shape was imaged in the upper mantle beneath Changbaishan by P-wave tomography, and was suggested as an upwelling of wet materials from the MTZ (Zhao et al., 2009). We have compiled geochemical data of Quaternary basalts from Changbaishan and the surrounding volcanic fields (e.g., Jingbohu and Kuandian), and found a spatial correlation between the basalt chemistry and the distribution of the low-velocity zone. Namely, the Ba/Th and Pb/U ratios of the basalts tend to decrease with increasing distance from Changbaishan. Furthermore, the basalts from Changbaishan have Sr, Nd, and Pb isotopic ratios similar to the EM1 endmember and the rests are from more depleted source.

One possible source of the EM1-like component is the lower part of the sub-continental lithospheric mantle (SCLM). However, this is unlikely because the lower part of the SCLM beneath NE China formed in Cenozoic times, precluding prolonged isotopic ingrowth. Alternatively, the component was proposed to be derived from the MTZ. In the subducted materials, K-hollandite in metamorphosed sediments can be a major reservoir of incompatible elements such as Sr, Ba, and Pb. Elements released by breakdown of sedimentary K-hollandite would be high-Ba/Th and Pb/U, and thus, a suitable metasomatic agent to form EM1-like mantle in the MTZ (Rapp et al., 2008). Because the formation of the EM1 isotopic signature requires a timescales of >1 Ga, sediments in an ancient stagnant slab, as well as those in the Pacific plate stagnant slab, may have been involved in the source materials for the Changbaishan basalts.

Assuming that the age of the ancient slab sediment is 1.5 Ga, the isotopic ratios of the Changbaishan basalts can be explained by mixing of a depleted mantle with a 0.5% sediment component which consists of a 1:2 to 1:3 mixture of the recent and the ancient sediments. The MTZ beneath NE China is remarkably hydrous, as evidenced from the electrical conductivity observations (Kelbert et al., 2009). Therefore, it is plausible that a hydrous mantle plume ascended from the hydrated MTZ, and that partial melting occurred in the ascending plume in the asthenospheric mantle, leading to the basaltic magmatism at Changbaishan and its surrounding volcanic fields.

New insights from pumice-rich submarine density currents from caldera-forming eruptions in the Izu Bonin arc (ODP 126)

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The Sumisu rift in the Izu Bonin arc was the focus of numerous studies in the late 1980s. During the ODP expedition 126, the upper arc was piston-cored to depths down to 250 mbsf. Most research was focussed on the forearc, with few investigations addressing the enormous volume of volcaniclastic deposits at sites 790 and 791 in the rift basin, and site 788 on the rift shoulder. At site 790C, the piston cores reached 275 ka at 180 mbsf, and sampled numerous units of silicic pumice lapilli developed in beds up to several 10s of m thick, and interbedded with units of silicic and basaltic ash and hemipelagic mud. Careful analysis of the stratigraphy from core to core allows reconstruction of the major eruption sequences, although many of the very thick pumiceous beds were partially disturbed during core recovery, artificially increasing their thickness, and creating false bed boundaries. From our new logging data from legacy samples stored at the Kochi Core Center, we present a first attempt at stratigraphic correlation of beds throughout the rift basin, and discuss the origin of the pumice lapilli beds. Textural analyses, including of grain size, grain shape, componentry and pumice vesicularity were carried out to characterise the most recent pumice lapilli beds, in addition to clast, glass and mineral geochemistry. This new dataset allows correlation of strata across the rift basin with high confidence, underpinning our analysis of the style and environment of eruption, as well as of transport processes, involved in producing the pumice lapilli beds. We expect the pumice lapilli beds to have been derived from caldera-forming eruptions and by post-eruptive resedimentation, and discuss the probable water depth at the vent during eruption. This work applies modern textural and geochemical studies to legacy cores, showing the long-term value (already 20 yrs after collection) of samples from coring the shallow crust.