4th International Workshop on Collapse Calderas

September 23-29, 2012, Vulsini Calderas, Italy

Commission on Collapse Calderas

IAVCEI

MEETING SCHEDULE and CONTRIBUTIONS

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IUGG: International Union of Geodesy and Geophysics

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AIV: Associazione Italiana di Vulcanologia

INGV: Istituto Nazionale Geofisica e Vulcanologia

DPC: Dipartimento Protezione Civile

Comune di Bolsena

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WORKSHOP SCHEDULE

SEPTEMBER 23rd

14:00 – Departure from Termini Station, Roma

16:30 – Arrival in Bolsena

17:00 -18:00 – Registration

18:00 -20:00 – Icebreaker party

20:30 -22:00 - Dinner

DAY 1 - SEPTEMBER 24th

Auditorium Comune Bolsena

INTRODUCTION

► 9:00 -9:30 - IAVCEI President: Cas R.
IAVCEI Secretary: Martì J.
Workshop Organizers: Acocella V., Geyer A., Palladino D.

SESSION 1: Caldera context and structure

Conveners: Martì, Gudmundsson, Stix

► 9:30 -10:00 - A comprehensive classification of collapse calderas (*keynote*)
Martí J., Geyer A., Acocella V., Aguirre-Díaz G., Cas R.

► 10:00 -10:30 - Bonanza, an "extreme" resurgent ignimbrite caldera in the San Juan Mountains, Colorado (*keynote*)
Lipman P.W., McIntosh W.C., Zimmerer M.J.

► 10:30 -10:50 - Caldera structure, amount of collapse and erupted volumes: the case of Bolsena Caldera, Italy
Acocella V., Palladino D.M., Cioni R., Russo P., Simei S.

► 10:50 -11:10 - Analogue Caldera Collapse Experiments: An Investigation of Topographic Load as Applied to Near-Ridge Seamounts.
Coumans J.P., Stix J.

11:10 -11:30 - Coffee break

► 11:30 -12:30 – Session 1 discussion

12:30 -14:00 – Lunch

SESSION 2: Caldera formation and evolution

Conveners: Geshi, Lipman, Geyer

► 14.00 -14:30 - Structural development in matured collapse caldera: from structural control to erosional control (*keynote*)
Geshi N., Acocella V., Ruch J.

► 14:30 -14:50 - Kinematic analysis of vertical collapse on volcanoes using experimental models time series
Ruch J., Acocella V., Geshi N., Nobile A., Corbi F.

► 14:50-15:10 - Development of the Oligocene Indian Peak caldera, Great Basin, USA
Christiansen E.H., Best M.G.

► 15:10 -15:30 - Thermomechanics of caldera formation in large silicic systems
Gregg P.M., de Silva S.L., Grosfils E.B.

► 15:30 -15:50 - Improved Mechanical Insights Into Ring Fault Initiation and Caldera Formation
Grosfils E.B.

► 15:50 -16:10 - Caldera collapse mechanisms and caldera variations
Komuro H.

16:10 -16:30 - Coffee break

► 16:30 -17:30 – Session 2 discussion

POSTER SESSION

► 17:30 -18:30 - Oral introduction to the posters (5 min. each)

(Hotel Royal, Bolsena)

► 18:30 -19:30 – Poster presentation and discussion

Permian ignimbrite eruption and caldera evolution in a Variscan post-collisional setting: the Góry Suche Rhyolitic Tuffs, Intra-Sudetic Basin, SW Poland
Awdankiewicz M., Awdankiewicz H., Kryza R.

dMODELS: A MATLAB software package for Modeling Crustal Deformation
Battaglia M., Cervelli P.F., Murray-Moraleda J.R.

Non-negative Matrix Factorization: further applications to volcanoes in Ethiopia, Chile and Japan
G. Cabras, R. **Carniel**, J. Jones, M. Takeo

Volcanology of Taney Seamount A, Northeast Pacific Ocean
Coumans J.P., Clague D.A, Stix J.

The Vicuña Pampa Volcanic Complex, Southern Central Andes
Guzmán S., **Martí** J., Petrinovic I., Montero C., Brod A., Grosse P.

Post-supereruption intrusive magmatism at Silver Creek caldera (Black Mountains, western Arizona, USA): Timing, duration, processes, and relationship to the Peach Spring Tuff
McDowell S.M., Miller C.F., Ferguson C.A., Mundil R., Wooden J.

1993-2011 InSAR measurements at Aso caldera (Japan)
Nobile A., Ruch J., Acocella V., Sansosti E., Borgstrom S., Siniscalchi V., Aoki Y.

The Complex, 4.6ka Fogo A Caldera Forming Plinian Eruption, São Miguel, Azores Islands, and Relevance to Understanding the Eruption Style and Transportation Processes
Pensa A., Cas R., Porreca M., Giordano G.

Volcano-tectonic architecture of a Caldera Complex, Karthala volcano, Grande Comore: new field observations
Poppe S., Kervyn M., Soulé H., Cnudde V., De Kock T., Jacobs P.

Sierra de Apas, an intraplate caldera in extrandean Argentine Patagonia
Remesal M.B., Salani F.M., Cerredo M.E.

Structures of Rabaul caldera: new insights from numerical and analogue models
Ronchin E., **Geyer** A., Saunders S., Dawson J., Martì J.

Calderas associated to the Miocene Pire Mahuida Volcanic Field, northern Patagonia, Argentina
Salani F.M., Chernicoff C.J., Remesal M.B.

The Diamante caldera – Maipo Volcano complex: a potential hazard in the central Andes (34° 10´S)
Sruoga P., Feineman M.

Asymmetric caldera collapse: an example from Faial Island (Azores, Portugal)
Trippanera D., Porreca M., Ruch J., Pimentel A., Acocella V., Pacheco J., Salvatore M.

Collapse, eruption and products of the crystal rich, >1000 km^3, Permian Ora ignimbrite and caldera super-eruption, Southern Alps, northern Italy
Willcock M., **Cas** R., Giordano G., Mattei M., Morelli C., Hasalova P.

Relationships between the late Cenozoic caldera distribution, gravity and aeromagnetic data, in the NE Honshu arc, Japan
Yoshida, T., Prima O.D.A., Kudo T.

20:00 -22:00 - Dinner

DAY 2 - SEPTEMBER 25th

Auditorium Comune Bolsena

SESSION 3: Caldera deposits
Conveners: Cas, Palladino, Sulpizio

► 9:00 -9:30 - Using the stratigraphic record to understand the nature of caldera collapse (incremental vs catastrophic), the way calderas are constructed, and the contrasting spatial and temporal scales for big and small calderas (*keynote*)
Cas R., Giordano G., Martì J.

► 9:30 -9:50 - Reinterpretation of deposits and eruption sequence of the Otowi Member, Bandelier Tuff Formation, Valles Caldera, Jemez Mountains, New Mexico
Self S., Wolff J., Cook G.

► 9:50 -10:10 - The ignimbrite sequence of Guanajuato, Mexico: Evidence of a collapse caldera in the southern Sierra Madre Occidental.
Aguirre-Díaz, G.J., Tristán-González, M., Martí, J., Martínez-Reyes, J.J., Labarthe-Hernández, G.

► 10:10 -10:30 - What lithic-free eruptions tell us?
Sulpizio R., Groppelli G., Norini G., Carrasco-Nuñez G.

► 10:30 -11:10 - Session 3 discussion

11:10 -11:30 - Coffee break

SESSION 4: Caldera magmatic processes

Conveners: Cole, Self, Yoshida

►11:30 -12:00 - Caldera collapses and magma-chamber compartments
Gudmundsson A. (*keynote*)

► 12:00 – 12:20 - Magmatic Perturbations Induced by Caldera Collapse in the Okataina Volcanic Complex, Taupo Volcanic Zone, New Zealand
Cole J.W., Deering C.D., Klemetti E., Bachmann O., Burt R.M.

► 12:20 – 12:40 - Subvolcanic lateral intrusions and the 1968 caldera collapse of Fernandina volcano, Galapagos Islands.
Bagnardi M., **Amelung** F.

► 12:40 -13:20 – Session 4 discussion

13:20 -15:00 – Lunch

SESSION 5: Caldera unrest

Conveners: Amelung, Carniel, Battaglia

► 15:00 -15:30 - Caldera supervolcanoes, resurgence, and mineralization (*keynote*)
Stix J., Kennedy B., Wilcock J.

► 15:30 - 15:50 - Full exploitation of active ground deformation field at Yellowstone Caldera reveals via Advanced SBAS DInSAR approach
Pepe A., Tizzani P., Zeni G., Battaglia M., Lanari R.

► 15:50 -16:10 - On the long term non-Newtonian behaviour of resurgent calderas: The 1982-2010 Campi Flegrei (Southern Italy) case study
Tizzani P., **Castaldo** R., Manconi A., Manzo M., Pepe A., Pepe S., Sansosti E., Solaro G., Lanari R.

► 16:10 -16:30 - DInSAR deformation analysis of summit calderas
Solaro G., Casu F., Manzo M., Pepe A., Pepe S., Sansosti E, Tizzani P., Lanari R.

► 16:30 -16:50 - The Bolsena-Torre Alfina geothermal field: a case of caldera-related “blind” geothermal resource
Giordano G., Tescione I., Todesco M.

► 16:50 -17:10 - Active resurgence at Siwi caldera (Vanuatu): new insights on the structure and activity of the Yenkahe horst
Brothelande E., Lénat J.-F., Merle O., Peltier A., ANR-Vanuatu team

17:10 -17:30 - Coffee break

► 17:30 -18:30 – Session 5 discussion

► 18:30 -19:30 – **Field Trips:** introduction the Bolsena, Latera and Vico excursions
Acocella V., Palladino D.M., Giordano G., Cioni R., Cas R.

20:00 -22:00 - Dinner

DAY 3 - SEPTEMBER 26th

9:00 -18:30 - Field Excursion to **Bolsena Caldera** (see excursion guidebook)
Excursion leaders: Palladino D.M., Cioni R., Acocella V.

20:00 -22:00 - Dinner

DAY 4 - SEPTEMBER 27th

8:30- 18:30 - Field Excursion to **Latera Caldera** (see excursion guidebook)
Excursion leader: Palladino D.M.

20:00 -22:00 - Dinner

DAY 5 - SEPTEMBER 28th

8:30 -16:00 - Field Excursion to **Latera Caldera** (see excursion guidebook)
Excursion leaders: Giordano G., Cas R.

►17:00-19:00: summary and outcome of the workshop.

20:00 -21:30 - Dinner

21:30 23:30 – Wine-tasting session.

SEPTEMBER 29th

9:30 - Departure from Bolsena (stop to Sutri amphitheatre)
12:30 – Arrival to Roma Termini

Caldera structure, amount of collapse and erupted volumes:
the case of Bolsena Caldera, Italy

Acocella[1] V., Palladino[2] D.M., Cioni[3] R., Russo[2] P., Simei[2] S.

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Calderas are common on volcanoes, but their structure is seldom visible. The 19 km wide Bolsena Caldera, Italy, formed between 0.6-0.2 Ma. The largely preserved structural rim and subsurface data make Bolsena ideal to investigate caldera structure in relation to the subsidence and erupted volume. In this paper, we use remote sensing, field analysis, and available subsurface data. At the surface, the caldera passes from a downsag (south rim) to a narrow and densely faulted area (north rim), with outer normal and inner reverse faults. The caldera structure on the widely faulted east rim appears scale-dependent, with a staircase-like fault zone (larger scale), horst and graben-like structures (intermediate scale) and domino-like structures (smaller scale). Subsurface data indicate asymmetric collapse, with a northward increase in subsidence, ranging from diffuse (to the south) to focused (to the north) deformation at the surface. The collapse rate, constant between ~490-175 ka, was more than magma output between ~330-130 ka, highlighting significant (~200 m) and prolonged (~200 ka) post-eruptive subsidence. As the nearby Latera Caldera (west rim of Bolsena) was mostly active between ~265-160 ka, much of the subsidence at Bolsena may be related to this activity, suggesting a common magmatic reservoir. The subsidence-related structural variations along the caldera rim and the significant post-eruptive subsidence found at Bolsena have not been found in other calderas.
Session 1

The ignimbrite sequence of Guanajuato, Mexico: Evidence of a collapse caldera in the southern Sierra Madre Occidental.

Aguirre-Díaz, G.J.[1], Tristán-González, M.[2], Martí, J.[3], Martínez-Reyes, J.J.[4], Labarthe-Hernández, G.[2]

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Guanajuato is better known as an important gold and silver mineral district of Mexico that has been exploited since the 16th century until now. Thus, geologic studies have been carried out in this place since decades ago. Stratigraphy and structures are well established, and major faults and vein systems are precisely known. The series include a Mesozoic metamorphosed volcano-sedimentary sequence, which has been interpreted as a tectonically accreted terrane; a >1000 m thick red beds sequence, apparently Eocene, are interpreted as fanglomerates filling a continental basin; and a mid-Tertiary volcanic sequence composed of ignimbrites, surge deposits, and andesitic lavas and rhyolitic lava domes. The surges and ignimbrites in particular have been little studied with a volcanological approach, and have been misinterpreted by some authors as sedimentary sandstones (Loseros Formation), rhyolitic lavas (Bufa rhyolite), and sedimentary conglomerates (Calderones Formation). Randall (1994) recognized these units as volcanic rocks and has suggested a caldera source. Our studies show that these units correspond to two main pyroclastic flow sequences, one formed by the Loseros-Bufa units, and the other by the Calderones unit. The former is rhyolitic and the later andesitic-dacitic. Loseros is composed of a series of thin-bedded to laminated pyroclastic surge deposits in continuous and concordant contact with overlying Bufa massive ignimbrite. Calderones is composed of a series of thin-bedded and lithics-rich pyroclastic surge deposits and thin ignimbrites that changes upward to more massive and thicker ignimbrites. The first of these upper ignimbrites includes heterolithologic co-ignimbrite lithic lag breccias at near vent sites. On the basis of the distribution and volcanic stratigraphy observed in these pyroclastic units, it is evident that these series are products of a caldera located next to the City of Guanajuato and within the mineral district.

Session 3

Subvolcanic lateral intrusions and the 1968 caldera collapse of Fernandina volcano, Galapagos Islands.

Marco Bagnardi, Falk Amelung

Division of Marine Geology and Geophysics, University of Miami, Miami Florida, USA. (famelung@rsmas.miami.edu)

The 1968 caldera collapse of Fernandina volcano, Galapagos, was one the largest collapses at a basaltic volcano in historic times. This event is enigmatic because the associated eruption was relatively small with the volume of the erupted magma corresponding to only 1 % of the collapse volume. Here we present Synthetic Aperture Radar (InSAR) measurements of the surface deformation at Fernandina between 2003 and 2010 that provide new insights in Fernandina's plumbing system and the nature of the caldera collapse.

Through the analysis of spatial and temporal variations of the measured radar line-of-sight displacement we identify multiple sources of deformation beneath the summit and the southern flank, which are active on different time scales. At least two sources at ~ 1 km and ~5 km below sea level are considered to represent permanent zones of magma storage given their persistent or recurrent activity. Our data also provide evidence for two subvolcanic lateral intrusions from the central storage system (in December 2006 and August 2007). Withdrawal of magma from the plumbing system to feed lateral intrusions could have provided the void for the 1968 caldera collapse. Subvolcanic lateral intrusions could also explain the several meters of uplift that occurred at Punta Espinoza in 1927 and Urvina Bay in 1954.

Session 4

Permian ignimbrite eruption and caldera evolution in a Variscan post-collisional setting: the Góry Suche Rhyolitic Tuffs, Intra-Sudetic Basin, SW Poland

Marek Awdankiewicz[1], Honorata Awdankiewicz[2], Ryszard Kryza[1]

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The Góry Suche Rhyolitic Tuffs (GSRT) are moderate-volume pyroclastic deposits (several tens of cubic km, DRE) of Permian age (c. 290 Ma). The tuffs reflect a major volcanic event recorded in the Permo-Carboniferous succession of the Intra-Sudetic Basin, a late Palaeozoic intra-continental post-collisional through in the eastern part of the Variscides. The GSRT comprise bedded tuffs at the base, followed by massive tuffs, non-welded to welded near the top. This sequence is a product of plinian-type eruption. The bedded tuffs were deposited by pyroclastic fall and surges during the initial stages, whereas the massive tuffs are ignimbrites related to a major, pyroclastic flow-forming stage of the eruption. A SHRIMP study of five tuff samples show that zircon assemblages are heterogeneous, with abundant xenocrysts. A significant admixture of inherited components in the tuffs can be linked to mixing of juvenile tephra with basinal sediments upon the eruption and emplacement of the tuffs. However, abundant rhyolitic detritus (including ignimbrite fragments) in sedimentary rocks above the GSRT indicate that the tuffs were partly eroded shortly after deposition. Lithological similarities, bulk-rock geochemistry and SHRIMP zircon data suggest that the eruption site of the GSRT may be linked with a belt of diatremes in adjacent Carboniferous deposits. Geological evidence, e.g. the structure of the basin fill, thickness variation of the ignimbrites, distribution of subvolcanic intrusions, suggest also that the caldera, c. 10 km in diameter, formed at the southern prolongation of the diatreme belt, as a consequence of the ignimbrite eruption. Subsequent volcanic activity in this area included the emplacement of trachyandesitic and rhyolitic laccoliths / sills (dated at c. 283 Ma) at the base of ignimbrites along the caldera margins, as well as phreatomagmatic and effusive basaltic andesite eruptions from monogenetic volcanic centre(s) inside the caldera.
Session 3

dMODELS: A MATLAB software package for Modeling Crustal Deformation

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We have developed a MATLAB software package for the most common models used to interpret deformation measurements near faults and active volcanic centers. The emphasis is on analytical models of deformation that can be compared with data from the Global Positioning System (GPS), InSAR, tiltmeters and strainmeters. Source models include pressurized spherical, ellipsoidal and sill-like magma chambers in an elastic, homogeneous, flat half-space. Dikes and faults are described following the mathematical notation for rectangular dislocations in an elastic, homogeneous, flat half-space. All the expressions have been checked for mathematical errors and typos that might have been present in the original literature, extended to include deformation and strain within the Earth's crust (as opposed to only the Earth's surface) and verified against Finite Elements models.
Session 5

Active resurgence at Siwi caldera (Vanuatu): new insights on the structure and activity of the Yenkahe horst

Brothelande E.[1], Lénat J.-F. [1], Merle O. [1], Peltier A.[2], ANR-Vanuatu team

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The Siwi caldera is an elliptic depression (~4.5 x ~7.5 km) on the south-east part of Tanna Island (Vanuatu). Formed by a recent major ignimbrite eruption (<20 kyr from erosion pattern, Nairn et al., 1988), this caldera has focused the recent volcanic activity on the island since then and currently hosts the association of an active volcano (Yasur) and a resurgent block (Yenkahe horst). The N65-trending Yenkahe horst, rising 200-300 m above the caldera floor, coincides with the elongation of the caldera and shows a 0.75 km-wide axial graben. Carbon dating of uplifted coral reef limestone indicates a mean uplift rate of the horst of 156 $mm.yr^{-1}$ for at least the last 1000 years (Chen et al., 1995). Geochemical studies show that the degassing flux of Yasur is compatible with the emplacement of large quantities of unerupted magma in the Siwi area (Métrich et al., 2011). However, the inner structure of the Yenkahe-Yasur complex and the exact relationships between the volcano and the horst are still poorly known.
A great variety of data has been collected during various campaigns carried out between 2008 and 2012. We present here a detailed structural map of the Yenkahe-Yasur, and an analysis of the complex fault pattern on the horst, obtained from the combination of satellite images, aerial photography and field observations. New insights on the inner structure of the horst and its hydrothermal activity were also inferred from electrical data (Electrical Resistivity Tomography, TDEM, Self-potential), thermal data (Infrared remote sensing and subsurface temperature measurements), soil gas measurements and gravimetric data. The joint interpretation of this data set allows us to constrain the structure of the Yenkahe horst and to discuss the most probable resurgence mechanisms and the hazards in the Siwi area.
Session 5

Non-negative Matrix Factorization: further applications to volcanoes in Ethiopia, Chile and Japan

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Non-negative Matrix Factorization (NMF) is an emerging new technique in the blind separation of signals recorded in a variety of different fields. The application of these techniques is wide e.g. in speech recognition but only recently was it proposed to the analysis of volcanic signals. Volcanic tremor, the continuous seismic signal recorded close to a volcano, often consists of a mixture of signals having different and independent sources, both volcanic and non-volcanic, possibly including anthropogenic ones. In this talk we show that NMF is a suitable technique to separate such a mixture of foreground / interesting / target ”signals” from background / interference / undesired ”noise”. The first encouraging results obtained with this methodology were already published, separating high convection foreground signal from low convection background noise at Erta ’Ale lava lake in Ethiopia, and support a wider applicability in volcanic signals separation. In this talk we will discuss some of these possible further applications, with examples not only to Erta 'Ale volcano in Ethiopia but also to Villarrica volcano in Chile and Mt. Shinmoe-dake, Kirishima volcano in Japan.

Session 5

Using the stratigraphic record to understand the nature of caldera collapse (incremental vs catastrophic), the way calderas are constructed, and the contrasting spatial and temporal scales for big and small calderas.

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Calderas vary enormously in dimensions, magma compositions, and the frequency, scale and the style of eruptions. These variations are reflected in the stratigraphic record of calderas, and reflect different styles of caldera collapse and the way they are constructed. At one extreme, extremely large silicic explosive calderas record very large volume eruptions, occurring at a low frequency of every tens to several hundred thousand years, often producing extremely large volume ignimbrites with little or no plinian fallout deposits. (e.g the 30 x 25 km, rhyolitic, < 6 Ma Cerro Galan Caldera in the Andes of northwestern Argentina, the Permian Athesian Group of northern, Yellowstone caldera). By contrast smaller calderas are marked by prolonged eruption cycles, consisting of frequent relatively small volume explosive fallout and ignimbrite forming eruptions, (e.g. the phonolitic Las Cañadas Caldera system of Tenerife, and the Vico Caldera in central Italy). The erupted volumes of individual eruptions are small but seem capable of producing an increment of caldera collapse, and cumulatively produce a caldera during a single cycle of spaced eruptions. Repeated cycles produce a composite caldera complex (e.g. Las Cañadas). Small calderas seem to require a shorter time to produce a critical volume of eruptible magma than large calderas. Why? The likely causes include the conditions in the crustal magma source regions (first cycle and primitive, or polycyclic and depleted), the volatile content of the magmas produced (affects buoyancy and explosiveness), the volume of magma produced and/or available in the deeper source, and the tectonic stress field, which influences the ability of magmas to rise through the crust, and may act to create a tectonic (decompressional) trigger that initiates eruption. Large shallow magma chambers are likely to be more susceptible to tectonic triggers to initiate eruption than small ones.

Session 3

Development of the Oligocene Indian Peak caldera, Great Basin, USA

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The Indian Peak-Caliente caldera complex was a major focus of explosive silicic activity in the subduction-related Great Basin ignimbrite province during a middle Cenozoic ignimbrite flareup. The Indian Peak caldera is the largest and formed 30 Ma when an estimated 5,900 km^3 of crystal-rich dacitic magma erupted as the Wah Wah Springs tuff. The magma erupted from a depth of about 7 km. The internal structure of the caldera has been exposed by basin and range faulting and geologic relations suggest the following sequence of events. 1. Surface tumescence as the magma chamber grew. 2. Eruption was triggered by failure of the roof on an inner reverse ring fault complemented by outer normal ring faults. 3. Down sagging of the rim accompanied initial subsidence. 4. Landsliding of the walls caused brecciation of pre-caldera wall rock and entrainment in the boiling magma that erupted through it. 5. On the northern margin, a 6 km wide zone of tuff and Paleozoic rock slipped and brecciated on the downward sloping hanging wall. In the deeper levels of the sliding breccia, sufficient load existed to create intense cataclasis at the base of sliding blocks. 6.Magma continued to erupt through the thickening pile of intracaldera tuff, thereby consuming energy and constraining the lithic-rich ignimbrite within the topographic margin of the caldera. About 4.5 km of total subsidence occurred. 7. As vesiculation and fragmentation ceased, dacitic magma rose along the inner reverse ring fault and initiated resurgent uplift of the collar zone and reversal of displacements along the inner ring faults. 8. This magma solidified as porphyritic granodiorite that intruded intracaldera tuff. 9. Later, as much as 1 km of post-collapse, caldera-filling ignimbrites accumulated in the caldera moat between the topographic margin and resurgent intracaldera pile.

Session 2

Magmatic Perturbations Induced by Caldera Collapse in the Okataina Volcanic Complex, Taupo Volcanic Zone, New Zealand

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The Okataina Volcanic Complex (OVC) is one of the most active of the world and consists of at least two large caldera-forming eruptions of rhyolitic magma (Matahina ~ 330 ka ago and Rotoiti ~ 61 ka). Leading up to the Rotoiti event, pre-caldera eruptions tapped shallow reservoirs (4-8 km) filled with cold (~750°C) and wet (amphibole and biotite are ubiquitous) magma. Similar conditions prevailed in the magma chamber that was evacuated during the Rotoiti caldera-forming eruption. However, following the caldera collapse, nearly 20 kyrs passed before volcanic activity resumed (at ~45ka). Upon recommencing, eruptions were small (<4km^3), involved less silicic magma compositions (dacite-rhyodacite) and erupted from a relatively deeper (up to 10 km deep) and hotter (up to 950°C) reservoir. Over the past 35 kyrs, the eruptions have returned to the evacuation of cold (~750°C) and wet (amphibole- and biotite-bearing) rhyolite from shallow reservoirs.
This evolutionary trend is interpreted to be due to a process of rapid decompression-induced crystallization in the unerupted parts of the reservoir following the unloading and release of overpressure during and immediately after the caldera collapse. This rapid crystallization froze any left-over silicic mush zones, temporarily arresting the production of rhyolite in the mid- to upper-crust. This hypothesis is supported by bulk-rock trace element data, quench textures, and U-Pb/U-Th dating of zircons from a granitoid clast brought up to the surface by a younger eruption (1305 AD Kaharoa). For cold, wet silicic magmas to erupt again, a new upper crustal mush zone must have formed, requiring a prolonged (~20 kyr.) quiescence. This recent recovery in the system to production of cold-wet magmas indicates that the system has transitioned from post-caldera volcanism to pre-caldera volcanism, suggesting that the current state of the system may be conducive to another large, caldera-forming eruption.
Session 4

Analogue Caldera Collapse Experiments: An Investigation of Topographic Load as Applied to Near-Ridge Seamounts.

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Collapse calderas are the sub-circular volcanic depressions caused by the subsidence of the magma reservoir roof during an eruption. Scaled physical models of caldera collapse using flat topography have been instrumental in investigating the spatial and temporal development of calderas, in particular, the two distinctive sets of concentric ring faults. More recent analogue studies have investigated the effect of non-flat topography which alter the principle stress trajectories and resulting collapse structure. This provides a premise for investigating how naturally scaled topographic loads may affect caldera collapse in relation to shallow magma reservoirs.

Short chains of seamounts are common on the flanks of the pacific spreading ridge. The cones are circular in plan view with basal diameters varying from 5-10km, and heights varying from several hundred to over 1000m. The seamounts are often truncated with plateaus ranging in size from 2-5km, suggesting that a caldera has engulfed a large portion of the seamount which has been later filled. In some examples, the seamounts have calderas breaching towards the ridge. These later stage flank calderas reflect collapse as the plate has moved relative to a stationary magma source.

The objective of this study was to understand how a naturally scaled near-ridge seamount would affect caldera collapse from both a central, and offset position. Experiments from the centrally positioned cone result in:(1) More efficient subsidence along the inner, outward dipping faults, and (2) A preference to more symmetrical collapse patterns as indicated by the subsidence profile and circularity of the caldera. Experiments from the offset cone illustrate that collapse was asymmetric (trap door), with the center of greatest subsidence displaced from away from the region of largest topographic load. One possibility is that the cone acts as region of structural rigidity, therefore, behaving as a lever for trap door collapse.

Session 1

Volcanology of Taney Seamount A, Northeast Pacific Ocean

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The Taney Seamounts are a NW-SE trending, linear, near-ridge chain consisting of five submarine volcanoes located on the Pacific plate 300 km west of San Francisco, California. Morphologically, the seamounts are characterized as truncated cones with nested calderas decreasing in age towards the ridge axis. This study examines the volcanology of the largest and oldest seamount, (Taney-A, ~26 Ma), which is comprised of four well-exposed nested calderas. Each successive collapse event exposes previously infilled lavas, defining a relative chronology. The caldera walls and intracaldera pillow mounds were carefully sampled by the remotely operated vehicle (ROV) Doc Ricketts to obtain stratigraphically-controlled samples. Whole rock samples were analyzed for major and trace elements, volcanic glasses were analyzed for major and volatile elements(S, Cl), and plagioclase phenocrysts were separated for mineral and glass inclusion analysis. The Taney-A lavas and volcaniclastics are subalkalic mid-ocean ridge basalts (MORB) varying from more to less differentiated (6.0 – 8.2 wt. % MgO) with decreasing age. Incompatible elements and REE profiles normalized to primitive mantle suggest that the lavas are transitional to slightly enriched (0.1 – 0.3 wt. % K_2O; 1.1 – 2.2 wt. % TiO_2).
The presence of large, well defined calderas infer some form of shallow magma reservoir. The results indicate significant geochemical changes with eruption of new lava after a caldera forming event. The general trend from higher to lower incompatible element concentrations (K, P, Ti, REE) with relative time, as inferred from structural relationships, cannot be explained exclusively by fractional crystallization. Progressive changes in lava chemistry after a caldera forming event may be due to rejuvenation of the evacuated reservoir with primitive magmas which undergo differentiation and subsequent eruption into the recently formed caldera. New volatile data (CO_2, H_2O, Cl and F) from glassy inclusions in plagioclase may provide insights into the volcanology of caldera forming eruptions at the Taney Seamounts.
Session 4

Structural development in matured collapse caldera: from structural control to erosional control

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Calderas are depressions formed by the collapse of the roof of a magma chamber due to the extraction of magma. Because caldera evolution is driven by the subsidence of caldera floor bordered by ring faults, collapse calderas evolve by increasing their depth / diameter ratio. The goals of this study are understanding, organizing and summarizing the processes occurring during the formation of mature calderas, characterized by a double ring fault, and still undergoing progressive subsidence.

To properly characterize caldera evolution, a structural S/D (ratio between structural subsidence and ring-fault diameter; Ss/Ds), and a topographic S/D (ratio between topographic caldera depth and topographic caldera width; St/Dt), are considered. Some field observations in the recent caldera collapses and analogue experiments indicate that the evolution of S_t/D_t and S_s/D_s. The S_s/D_s becomes significantly different from S_t/D_t when S_s/D_s~0.33, while S_t/D_t and S_s/D_s show a similar increase at initial stages. While continuous caldera subsidence monotonically increases S_s/D_s, the erosion of the wall and the filling of the floor decrease S_t/D_t. Analogue experiments mimic the observed variation, evolving from a depression controlled by the activity of the double-ring faults to that controlled by the erosion of the wall and sedimentation at the floor. These natural and modeling results show that the control on the shape of mature calderas (S_s/D_s>0.07) and approaching S_s/D_s = 0.3-0.4 passes from a mainly structural to a mainly erosional control. Both S_t/D_t and S_s/D_s are needed to describe the evolution of a collapse and the processes accompanying it. Evaluating S_t/D_t and S_s/D_s allows proper description of the precise evolutionary stage of a caldera and of the relative importance of the structural and erosional processes and allows making semi-quantitative comparisons between evolutionary stages.

Session 2

The Bolsena-Torre Alfina geothermal field: a case of caldera-related "blind" geothermal resource

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The Torre Alfina geothermal field is located about 10 km north of the Quaternary Bolsena structural caldera margin. The area has been investigated since the 1970s (e.g. COSTANTINI *et alii*, 1984; BUONASORTE *et alii*, 1988; BARBERI *et alii*, 1994; CHIARABBA *et alii*, 1995, CHIODINI *et alii*, 1995; DOVERI *et alii*, 2010). The reservoir is a buried structural high made of Mesozoic-Cenozoic carbonatic sequences characterised by discontinuous secondary permeability and sealed by clay-rich alloctonous syn-orogenic flysch successions and Pliocene neo-authoctonous marine clays. The reservoir is locally highly productive, water-dominated and CO2-rich, with T at its top of 120°C. The origin of the heat source was not investigated in detail but generally attributed to some unidentified deep magmatic body, while the recharge was thought to derive from nearby emergent ridges made of Mesozoic-Cenozoic carbonatic sequences, similar to those drilled in the Torre Alfina reservoir.
We performed new structural and geological investigations and revised all geophysical and geochemical data available, as well as all data from the several deep-bore-holes drilled in the geothermal field, including productivity data.
Based on an updated conceptual model for the Torre Alfina geothermal field we performed numerical simulations in TOUGH2 code. Results indicate that deep circulation is forced by the geometry of the reservoir and by T and P gradients. We interpret the Torre Alfina field as formed dominantly by lateral advection of heat and mass from the Bolsena caldera deep system driven both by high T and by the greater depth at which reservoir rocks are downthrown by the volcano-tectonic collapse. Preferential fracture fabric in the deep carbonates allows the lateral heat transfer. The cap-rocks have excellent sealing characteristics allowing the preservation of heat in correspondence with positive structural traps.
A major outcome of this study is that where calderas downthrow reservoir-structures that extend beyond the caldera margins there is a potential for development of significant geothermal fields well away from the caldera margins and away from a direct heat source forming more or less blind resources for lateral advection.
Session 5

Thermomechanics of caldera formation in large silicic systems

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Utilizing new temperature-dependent viscoelastic models that incorporate a Mohr-Coulomb failure criterion, we find that the eruption trigger for the largest magma chambers is a function of the geometry of the overlying roof and the location of the brittle-ductile transition. In particular, the ductile halo created around the hot magma chamber buffers increasing overpressures and prevents pressure relief via magmatic injection from the magma chamber. As overpressure increases within the largest magma chambers, extensive uplift in the overlying roof promotes the development of through-going faults that may trigger eruption and caldera collapse from above. Specifically, we find that for magma chamber volumes > 10^3 km^3, and roof aspect ratios (depth/width) < 0.3, moderate magma chamber overpressures (< 30 MPa) will cause extensive through-going fault development in the overlying roof. This finding indicates that, for the largest chamber sizes, caldera formation may have an external roof-triggered mechanism with an overpressurized condition. This numerical result is consistent with observations from numerous locales, e.g., the Central Andes (de Silva and Gosnold, 2007; Salisbury et al., 2010), the Great Basin of Nevada (Best and Christiansen, 1991; Maughan et al., 2002), Yellowstone (Christiansen, 2001), the Southern Rocky Mountain Volcanic Field of Colorado (Lipman, 1984), and Toba (Chesner and Rose, 1991; Chesner, 2011). In these locations, ignimbrites from the largest eruptions lack precursory plinian fall deposits and exhibit ponding within the caldera, indicating early onset of caldera collapse and leading investigators to propose an external eruption trigger such as fault propagation through the roof (Sparks et al., 1985; de Silva, 1989a; de Silva, 1989b; Christiansen, 2001; Lindsay et al., 2001b; Maughan et al., 2002; Schmitt et al., 2003).

Session 2

Improved Mechanical Insights Into Ring Fault Initiation and Caldera Formation

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Elastic numerical models have become increasingly important for interpreting field data and gaining insight into caldera evolution, with emphasis for instance upon the process of ring fault formation in response to volcanic activity. Using an approach introduced nearly a century ago [1], most researchers investigating ring fault formation in response to the evolution of a subsurface magma reservoir have modeled the reservoir as a cavity subjected to over/underpressure in an otherwise unloaded elastic host [e.g., 2,3]. This approach is derived by balancing stresses acting orthogonal to the reservoir wall—i.e. subtracting the reference gravitational host rock (lithostatic) stress trying to collapse the chamber from the magma pressure pushing outward to keep it open—which zeroes out the wall-normal (applied in most models to all) gravitational loading effects. By reducing the model to an unloaded elastic host on the basis of a stress balance performed in only one direction, however, such a treatment inappropriately zeroes out the two wall-parallel components of the lithostatic stress tensor in the host; detailed elucidation of this argument under diverse geological conditions has demonstrated the implications for several key volcanological processes [4-9]. Such results strongly suggest that existing 'unloaded' numerical formulations used to explore ring fault formation under elastic conditions also introduce internal, potentially significant inconsistencies.

Here, retaining the full elastic stress tensor in the host, I re-examine the process of ring fault formation and compare the results to existing numerical and analogue solutions. Contrary to results reported previously [e.g., 2], external conditions such as regional extension or domal uplift are not needed for ring fault initiation to occur in response to reservoir overpressure. In addition, use of the full host rock stress tensor reconciles comparable numerical and analogue model results, resolving persistent concerns regarding the 'mismatch' between outcomes obtained from these two complementary model styles.

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Session 2

Caldera collapses and magma-chamber compartments

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A crustal magma chamber is normally a necessary condition for the formation of a major polygenetic volcano. But a magma chamber is also a necessary condition for the formation of a collapse caldera. Observational and theoretical results show that the conditions for caldera collapses are rarely satisfied. Even where a caldera exists, slip on the ring fault are rare in comparison with the frequency of magma-chamber ruptures and dyke or sheet injections in the volcano. For a collapse caldera to form, the appropriate shear-stress conditions must be reached in all the rock layers and units between the magma chamber and the surface in a zone that eventually becomes the ring fault. Because of the widely different mechanical properties of these layers and units, these conditions can, in principle, be reached only occasionally, as is confirmed by the general rarity of caldera collapses in active volcanoes.

When caldera collapses do occur, however, they may have large effects on the associated crustal magma chambers. More specifically, a caldera collapse may help generate compartments within the associated magma chamber. In particular, a nested collapse caldera, that is, a multiple caldera where one or more calderas are located partly or entirely within a larger and (usually, but not always) older caldera. The ring faults associated with the calderas are commonly with a very low permeability (some are occupied with ring dykes) with respect to magma flow and may contribute to dividing the chamber into compartments.

Flow of magma between compartments following a caldera collapse, or a large slip on an existing caldera, is thus unlikely. Not only do the ring faults act as barriers to lateral flow of magma, but the common density stratification in the chamber makes downward flow of low-density magma under the bottom of a piston-like part of a multiple caldera and into a different compartment unlikely. Thus, even if the original magma in the chamber before collapse had a generally similar composition, at least at the same depth levels in the chamber, the division of a chamber into compartments following the caldera collapses may result in different magma-evolution paths (through anatexis, fractionation, and stoping) in different compartments. Eventually, there may be compositionally quite different magmas in the different compartments; magmas that exchange heat but little if any matter over considerable periods of time. These compartments may thus be effectively closed thermodynamic systems.

Compartments of this type are common in various types of reservoirs, in particular in hydrocarbon reservoirs. They have, however, received little attention in volcanology. They are likely to be common and, especially, in magma chambers associated with nested calderas. Compartments are presumably one of the main reasons why in many volcanoes there may be eruptions at short intervals and from the same magma chamber with widely different compositions.

Session 4

The Vicuña Pampa Volcanic Complex, Southern Central Andes

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The Vicuña Pampa Volcanic Complex is located at the southeastern edge of the Altiplano-Puna Plateau. It is peculiar not only for its location, but also because of its composition, which varies from basalts to dacites. It has been interpreted as a collapse caldera by Rossello & Jones (1999) and Viramonte & Petrinovic (1999), based mostly in its caldera-like morphology. No calderas of this composition have been reported in the Central Andes, making the study of this centre really intriguing. No straightforward clues to classify this volcanic structure are found. The features that favour its interpretation as a collapse caldera are its subcircular shape, a central depression and the shallow slopes of the outer deposits. On the other hand, no pyroclastic deposits related to the complex, no ring faults and no deposit related to a caldera collapse episode have been found. The walls of the depression are formed by a ca. 12 Ma (Guzmán et al. in prep) sequence of basaltic to andesitic, massive to poorly stratified matrix-supported monolithologic volcanic breccias up to 300 m thick, overlain by at least two lava flows of basaltic to andesitic composition. The deposits within the depression are mostly covered by reworked material. Its eastern part is formed by igneous-metamorphic basement, whereas the central and western sectors show lava domes and volcanic breccias probably related to their repeated gravity driven collapse. In summary, although Vicuña Pampa has one of the most caldera-like shapes of the Central Andes, no deterministic features to definitely prove it are found.

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Session 1

Caldera collapse mechanisms and caldera variations

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Despite the sizes, magma compositions or eruptive durations, caldera collapse is divided into two types; overpressure type and underpressure type. The overpressure type calderas, which follow the surface doming, are characterized by polygonal outlines, whereas the underpressure type calderas are defined as circular calderas after the large eruptions. The polygonal caldera is identified as an apical depression rimmed with radial fractures and inward dipping normal faults. The circular caldera is characterized by outward dipping reverse boundary faults and a bell-jar type central collapse block (Komuro 1987; Roche 2000; Acocella 2001). These collapse types are modified by the shape or depth of the magma chamber, so that many caldera variations occur.
Variations of polygonal calderas: A spherical to vertically elongated overpressure magma chamber produces a wide radial fracture zone including a narrow and deep apical depression caldera. A penny shaped large overpressure magma chamber causes a large shallow polygonal caldera (Walter and Troll 2001). These calderas are controlled by radial fractures and normal faults, and then they always show polygonal outlines.
Variations of circular calderas: The bell-jar collapse block subsides into the deep seated spherical underpressure magma chamber accompanied with ring dike intrusions. The pure evacuation of a vertically elongated magma chamber causes a flat-floor shallow caldera collapse (Okamoto and Komuro 2009), whereas the catastrophic magma emission from the penny shaped large magma chamber produces a large piston-cylinder type, downsag type or trapdoor type caldera (Lipman 1997).
Cyclic calderas: Cyclic alternative inflation and deflation of the magma chamber produce a nested caldera or a peacemeal caldera (Troll et al. 2002). Most polygenic calderas might be in this type.
Session 2

Bonanza, an “extreme” resurgent ignimbrite caldera in the San Juan Mountains, Colorado

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Among large calderas associated with ignimbrite super-eruptions, the 33.2 Ma Bonanza caldera of the Southern Rocky Mountain volcanic field displays compositional and structural features that provide near-endmember examples of ignimbrite eruptive processes. Bonanza, source of a compositionally complex regional ignimbrite sheet erupted at 33.19±0.04 Ma, is a subequant resurgently domed structure ~20 km diameter that subsided >3 km during eruption of ~1,000 km^3 of ignimbrite. Among its exceptional features: (1) extreme compositional gradients in the associated Bonanza Tuff (mafic dacite to silicic rhyolite; 59-76.5% SiO_2); (2) multiple alternations of mafic and silicic zones, rather than simple progression from silicic to mafic; (3) compositional contrasts among outflow sectors (mainly rhyolite to east, dacite to west); (4) similarly large compositional diversity among postcollapse caldera-fill lavas and resurgent intrusions; (5) brief time span for the entire caldera cycle (33.2-32.9 Ma); (6) a uniquely steep-sided resurgent dome (dips of 40-50^o on west and 70-80^o on east flanks; (7) unique exposure levels due to later structural tilting and rugged present-day topography--from postcollapse lavas, to thickly ponded intracaldera ignimbrite and interleaved landslide breccia, down through precaldera volcanic floor, into underlying Paleozoic and Precambrian basement that are intruded by resurgent plutons.
Some near-original caldera morphology remains defined by present-day landforms (western topographic rim, resurgent core, ring-fault valley), while tilting and deep erosion provide exceptional three-dimensional exposures of fill, floor, and resurgent structures. An ~2.5-km-thick section of intracaldera ignimbrite on the western flank of the resurgent dome is complexly compositionally zoned (up to nine gradational alternations of rhyolite and dacite, interleaved with collapse-breccia lenses), underlain by caldera-floor intermediate-composition volcanics, and overlain by caldera-filling andesite to rhyolite lavas. Caldera-fill ignimbrite has been largely stripped from the southern and eastern flank of the dome, exposing large area of caldera-floor as a fairly coherent domed plate, bounded by ring faults with locations that are geometrically closely constrained even though largely concealed beneath valleys. Floor rocks are intensely shattered within ~100 m of ring faults, and upper levels of the floor are locally penetrated by dike-like crack fills of intracaldera ignimbrite.
Session 1

A comprehensive classification of collapse calderas

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Collapse calderas are volcanic depressions that result from the disruption of the magma chamber roof during an eruption or lateral intrusion of magma. Their formation implies a perturbation of the structure and dynamics of the associated magma chambers. Collapse calderas are present in any geodynamic environment and may be associated with a wide range of magma compositions. Caldera morphology and structure yield information on subsidence mechanisms, evolutionary stage of collapse and the associated magma chamber, while any eruptive product provides the clues on magma composition and eruption dynamics.
The term "caldera" has been commonly used to define certain sizes of collapses in volcanic areas, rather than a specific process. Moreover, several different classifications of collapse caldera have been proposed considering separately various aspects such as morphology, structure, composition, style of subsidence, size, eruption dynamics, or tectonic controls. However, the causative relationships between the resulting caldera types are not always well defined, thus causing confusion on the causes and results of each caldera process.
This study has two main goals. 1) First, we provide a timely definition for calderas: we propose to restrict the term collapse caldera to those cases in which there is a direct interaction of the structures controlling collapse with an underlying magma chamber, independently of its size. 2) We present a comprehensive classification of collapse calderas based on an event tree structure that considers a hierarchy of criteria that we analyse in a logical sequence. This classification allows identifying any collapse caldera as a function of its dynamic, geometric, evolutionary and compositional conditions.
Session 1

Post-supereruption intrusive magmatism at Silver Creek caldera (Black Mountains, western Arizona, USA): Timing, duration, processes, and relationship to the Peach Spring Tuff

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The Silver Creek caldera (southern Black Mountains, western Arizona, USA) is the source of the 18.8 Ma Peach Spring Tuff (PST), a >700 km^3 (DRE) high-silica ignimbrite that serves as an important stratigraphic marker in the southwestern United States (Ferguson et al., in press). A 30 km^2 suite of shallow plutons - the Moss porphyry (~62-68 wt% SiO_2) and Times porphyry (~72-77 wt %SiO_2) – and compositionally diverse dikes intrude the PST caldera fill. Enclaves (several cm to >2 m in diameter) are locally abundant in all intrusive units.

We used U-Pb zircon geochronology, whole rock and zircon geochemistry, and petrography to investigate the post-supereruption epizonal magmatic processes recorded by the intrusives, the timing and duration of this magmatism, and whether the PST and the intrusives are genetically linked. Consistently linear elemental trends, the presence of enclaves and rimmed/rounded feldspars throughout the intrusive complex, and zircon geochemistry suggest mingling and hybridization between magmas with trachyandesitic and Times-like compositions. High-precision CA-TIMS U-Pb zircon analysis of the Moss, Times, and feldspar porphyry dikes indicates that resurgent post-PST magmatism lasted ~200 ka. Two Moss samples yielded ages (18.78 +/- 0.13 Ma and 18.85 +/- 0.15 Ma) close to that of the PST (18.78 +/- 0.02 Ma, Ar/Ar, Ferguson et al., in press). Zircon from the Times and a feldspar porphyry dike were dated at 18.634 +/- 0.060 Ma and 18.662 +/- 0.054 Ma, respectively.

Although parts of the Times are similar to the PST outflow, most of the intrusives record no direct connection with the PST. The PST has distinctly higher concentrations of Zr and K_2O, and lower concentrations of Sr, than most of the intrusives. However, the Moss and intracaldera PST zircons share high-Ti, low-U rims, suggesting that both experienced reheating/remobilization. Whole rock isotopic analysis in progress will further elucidate intrusive-plutonic relationships and magmatic processes.

Session 4

1993-2011 InSAR measurements at Aso caldera (Japan)

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Aso caldera, Kyushu island (southern Japan), formed during four major explosive eruptions between 270 and 90 ka. Several volcanic vents are located in the central part of the caldera, among which the Naka-Dake, the only active, characterized by strombolian and phreatic activities, last eruption in May-June 2011.
We analyzed ground deformation at Aso processing a time series of 73 SAR images acquired by different sensors (ERS 1-2, ENVISAT and ALOS), using ROI_PAC software (Jet Propulsion Laboratory release). Interferograms span different time periods, over 19 years, from October 1993 to April 2011.
We observer alternating periods of uplift and subsidence associated to eruptions. For periods with consistent signal, we stacked velocity maps to increase the signal-to-noise ratio and improve the detection of deformation reducing errors due to atmospheric effects and random noise.
In particular, we focused our work on three periods for which steady ground deformation was detected:
1) From January 1996 to November 1998 (ERS data), subsidence of 1.5 cm/yr (LOS) occurred in the central part of the caldera beneath Naka-Dake area, just after the May 1994 – November 1995 eruption.
2) From October 2003 to June 2006 (ENVISAT data), uplift of 2-3 cm/yr (LOS) was observed in the central-southern part of the caldera. This period includes two eruptions, in January 2004 and April-August 2005.
3) January-April 2011 (last ALOS data), just before the last eruption, uplift of ~2 cm in the central part of the caldera and subsidence below Naka-Dake crater.
We calculated the source model for the deformations in these periods. Preliminary results suggest a 5-6 km depth source.
InSAR results are broadly consistent with available leveling data and models agree with the seismic data interpretation available in literature.
Session 5

The Complex, 4.6ka Fogo A Caldera Forming Plinian Eruption, São Miguel, Azores Islands, and Relevance to Understanding the Eruption Style and Transportation Processes

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Fogo Volcano is one of the most dangerous active volcanoes in the northern hemisphere. It lies in the centre of São Miguel Island in the Azores Archipelago, mid-Atlantic Ocean. The last major eruption of Fogo Volcano was the FOGO A eruption, dated 4.6 ka. The eruptive sequence is principally constituted by the well-known fall out deposits and poorly understood pyroclastic flow deposits. The eruption produced a high, unstable plinian eruptive column and consequent caldera collapse. New roadcuts made in 2011 along the southern flank of Fogo volcano, clearly exposed the complex relationships between the fall and the flow deposits and the paleotopography. At least two paleo-topography confined ignimbrites and surge deposits are instratified within the plinian fallout sequence, indicating that several partial collapses of the eruption column occurred during the eruption. The eruption culminated in the emplacement of a final climactic ignimbrite. The high particle concentration gravity driven flows were dispersed into paleovalleys to the north and south of the volcano, whereas the fallout deposits were dispersed all around the volcano, but mostly to the south. The maximum thickness of the massive poorly sorted ignimbrites is in the narrow paleo-valleys, whereas on adjacent paleo-highs they are thin and the deposit is represented only by surge ash deposits and stratified ignimbrite veneer deposits that thicken into the valley pond deposits. This valley pond and veneer geometry is well preserved along the southern flank of Fogo Volcano, whereas the northern part is almost totally covered by the ignimbrite related to the final collapse, overlying thin fallout deposits. This climactic ignimbrite is more than 50 meters thick in the north part and 30 meters in the south.

This complex stratigraphy suggests that during the time of the eruption the column was unstable, maybe due to a changeable eruption rate or due to a decrease in magma volatile content. This is supported by a change from white highly vesiculated pumices in the basal fallout, to less vesiculated, but compositionally similar black and banded pumices in the upper part of the succession.

Preliminary thermal remanent paleomagnetic (TRM) analysis carried out on the lithics in the ignimbrite deposits, there is an evident difference in the temperature of emplacement between the two intraplinian ignimbrites and the last major ignimbrite. The two intraplinian ignimbrites were hotter than the final ignimbrite, which could be related to a high juvenile content and a low lithics content of the intraplinian ignimbrites, as well as a more expanded flow state of the final pyroclastic flow, which would have flowed on a subdued topography largely infilled by the earlier pyroclastic flows. The obtained results give us a good overview from different aspects, of the dynamics occurred during the caldera forming FOGO A eruption.

Session 3

Full exploitation of active ground deformation field at Yellowstone Caldera reveals via Advanced SBAS DInSAR approach

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The Yellowstone volcanic field centered at the Yellowstone National Park, Wyoming, is one of the largest and most active silicic volcanic systems in the world similar to other volcanic fields such as Long Valley, California, and Phlegrean Fields, Italy.
The youthful volcanic history of Yellowstone was dominated by three cataclysmic caldera-forming eruptions in the past two million years. The youngest eruption, at 0.64 million-years-old, formed the 40-km-wide by 60-km-long Yellowstone caldera. Since the last cataclysmic eruption at least 30 dominantly ryholitic and basaltic lava flows, as young as 70 000 years old, have been erupted, covering much of Yellowstone.
Geodetic measurements of Yellowstone from 1923 to 2004 using precise levelling, GPS, and InSAR have revealed multiple episodes of caldera uplift and subsidence, with maximum average rates of ~1 to 2 cm/year generally centered at its two resurgent domes, Sour Creek and Mallard Lake. In addition, an area northwest of the caldera near Norris Geyser Basin experienced periods of substantial ground deformation. These spatial and temporal variations of the Yellowstone unrest also correlated with pronounced changes in seismic and hydrothermal activity.
In this work, the temporal variations of ground deformation in the context of the evolution of Yellowstone's volcanic features are analyzed, applying the SBAS-DInSAR technique on the 1992-2010 time interval.
The performed analysis relevant to the 1995-2010 DInSAR time series has revealed a complex scenario of detected deformation field. In particular, four main deformation trends characterized the dynamic of caldera region and surrounding area. From 1992 to 1995 a broad subsidence pattern affects the entire caldera region with maximum displacement in WSW – ENE direction along the major caldera axis (Mallard lake dome and Sour Creek dome). The detected ground deformation between 1995 -1998 reveals a new uplift phenomenon focused in the area at west of Sour Creek dome (Mud volcano). In the 1995 -2003 time interval the previous uplift event grows significantly involving the area of Norris Geyser Basin located outside caldera rim.
Finally the 2003 -2009 time interval is characterized by a spectacular inversion of caldera floor deformation. More specifically, the area affected by subsidence during the 1992 – 1995 time interval are involved in a new uplift event, jointly the area Norris Geyser Basin is also characterized by the inversion of ground deformation. According to previous studies, the performed analysis shows a spatial and temporal migration of deformation field whose oscillations can be seen as the breath of volcano.
Session 5

Volcano-tectonic architecture of a Caldera Complex, Karthala volcano, Grande Comore: new field observations

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Karthala volcano, Grande Comore, is one of the worlds' largest active alkali-basalt intraplate shield volcanoes. It possesses a 3.5 x 2.8 km² large summit caldera complex. Limited study has been carried out to unravel its structure and geometry, collapse chronology and changes caused by recent eruptive phases. Exploratory missions to the Karthala summit in 2011 led to an updated overview of the volcano-tectonic structures, an analysis of the local principle stress orientations and a preliminary stratigraphy of the 400 m deep exposed rock sequence.
Caldera walls in the whole complex consist of massive alkali basalt flows with intercalated weathered pyroclastic layers, topped by scoria and tuff cones. The caldera floor itself is covered by volcanic ash, lapilli, and scoriaceous ancient flows. Three overlapping caldera's build the main structure of the complex, with vertically-subsided blocks along the main caldera bounding faults. Several intracaldera structures represent a smaller scale of collapse: several intracaldera graben-like structures are observed, evidencing secondary syn- or post-collapse extension; 'Changouméni', a nested pit crater in the Northern caldera, has been almost completely filled with pyroclastics and lava flows over the last fifty years; two deep explosion craters, named 'Chahalé', located at the intersection of the 3 main caldera structures, expose a sequence of thick alkali basalts, cross-cutting dykes, small-scale eruptive cones and former caldera levels.
An active hydrothermal system is evident from degassing fissures inside Chahalé, Changouméni and in the area between both, and is suggested to have controlled the phreatic nature of recent eruptions, their explosivity contrasting with the effusive Hawaiian-style character generally associated with Karthala. Caldera-bounding structures, eruptive and fumarolic fissures, dykes as well as intra-caldera extensional faults indicate a minor E-W and two major N-S and N135°S volcano-tectonic directions, the latter concurring with previously identified regional stress orientations and rift zone's orientations on Karthala's flanks.
Session 2

Sierra de Apas, an intraplate caldera in extrandean Argentine Patagonia

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Several Miocene large bimodal complexes aligned along WNW-ESE trending belt were built over the mostly Oligocene Somún Curá basaltic plateau, in northern Argentine Patagonia. Trachyte- basaltic associations related to big cauldrons are typical of this post plateau stage. Extensive field mapping and petrologic studies were carried out on Apas Volcanic Complex (AVC), a Neogene (24-19 Ma) bimodal volcanic center. The volcanic edifice has a sub-circular shape with 32 km diameter and shows an asymmetric profile (1100m N flank-800 m S flank). The central area is composed of trachytic volcanics related to two effusive phases (a-olivine trachyte and b- quartz trachyte lavas). Mesosilicic pyroclastic flows are interlayered in the NE sector, whereas rhyolite lavas displaying flow banding occur interbedded in the SW area of the central zone. The most characteristic feature of AVC is the radial pattern of trachytic dikes emanating from the center of the volcano. Outer concentric zone is represented by a basaltic facies (alkaline basalts) which constitutes the main flanks of the structure. Aligned strombolian small cones can be distinguished in this sector. Peripherically, in the northern caldera rim, two trachytic lava domes occur: Cerro Colorado (NE) and Marabella (NO). A regional NW-SE lineament controls the southeastern caldera rim. Based upon geochemical studies, trachytes and basalts, define a bimodal alkaline cogenetic suite with an intraplate signature. The AVC, like others post plateau complexes, would be related to an extensional environment, as a consequence of major plate reorganization occurred along Pacific margin of the South America plate.

Session 2

Structures of Rabaul caldera: new insights from numerical and analogue models

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Understanding the structures of active calderas is fundamental for the interpretation of deformation data and thus for volcanic hazard assessment. Rabaul Caldera is an active volcanic complex whose recent activity culminated in 1994 with the twin eruption of Tavurvur and Vulcan volcanoes that led to the evacuation of Rabaul city.

The current structure of Rabaul Caldera is the result of multiple caldera forming events. The last one occurred 1.4 ka ago and resulted in an elliptical plan-view shape collapse structure of 9.5x7 km that nowadays hosts most of Blanche Bay. In its interior, the concentric annular shape of the seismicity, registered between 1971 and 1994, revealed elliptical outward-dipping active faults whose role, both during the last caldera forming event and during the 1994 eruption, is not clear. In order to shed some light, we have compared the collapse structures resulting from our analogue models to those of the 1.4 ka collapse event. From our results we are able to:

– constrain the depth of the magma chamber that could have caused the collapse

– state that the Rabaul concentric outward-dipping faults correspond to those bordering the first-formed inner depression that appears when reproducing a caldera collapse with an analogue model. Consequently, these concentric outward-dipping faults were formed during the 1.4 ka collapse event and reactivated between 1971 and 1994 by the new input/migration of magma in the system.

Finally, the geometric information obtained about the structures of Rabaul Caldera are applied to develop a 3D model of the area using the Finite Element Method (FEM) in order to assess the effects of the structure parameters on the surface deformation field. The 3D model includes the most relevant structures formed during the various collapse events as well as the topography and the different mechanical properties of the subsurface materials.

Session 1

Kinematic analysis of vertical collapse on volcanoes using experimental models time series

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Volcanoes are often associated with vertical collapse, due to deeper magma withdrawal. Calderas are the most notable type of vertical collapse, on the summit of volcanoes. However, collapses have been observed and monitored only at Miyakejima (Japan; 2000), Dolomieu (Reunion; 2007) and Fernandina (Galapagos; 1968), highlighting our limited knowledge on the kinematic behaviour of caldera collapse. Here we use experimental models to investigate their kinematic evolution. We extract velocity and strain fields using the Particle Image Velocimetry (PIV) technique, generating time series. Vertical collapses undergoing constant subsidence velocity show three main kinematic behaviours in our models: (1) continuous collapse, whose velocity is similar to the source subsidence velocity; (2) incremental collapse, with episodic (stepwise) accelerations along pre-existing ring structures; (3) sudden collapse, resulting from the upward migration of a cavity, only for T/D >2 (T and D are the depth and width of the magma chamber, respectively) and without ring structures. The velocity in the collapsing column may increase up to four orders of magnitude with regard to the constant subsidence velocity of the source. Comparison to nature suggests that: (1) there are close kinematic similarities with monitored collapse calderas, explaining their incremental subsidence after the development of ring structures; (2) sudden pit crater formation is induced by the upward propagation of cavities, due to magma removal at depth and in absence of ring structures; (3) all these types of vertical collapses have a consistent mechanism of formation and kinematic behaviour, function of T/D and the presence/absence of ring structures.
Session 2

Calderas associated to the Miocene PireMahuida Volcanic Field, northern Patagonia, Argentina

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In northern Patagonia (ca.42º S), in between the eastern end of the Andean arc and the beginning (68º 30´W) of the intraplate Somún Curá Plateau, it is exposed a volcanic field of 800 km^2 and approximately 100 km^3 of mainly acidic rocks, the most common facies being pyroclastic and lavic. Subordinate in volume, basaltic flows overlie the sequence of acidic rocks. This sequence makes the bulk of the sierra Pire Mahuida. A regional tectonic control is evidenced by the alignment of several Miocene bimodal volcanic complexes along a WNW-ESE trend, including the volcanic field studied herein. This field was built through several magmatic stages from 21 to 18 Ma, and it is mainly related to two volcanic structures and minor fissural vents, i.e.
a- A series of rhyolite lava domes following a sub-circular pattern define most of the main caldera boundaries. Airborne magnetic and gamma-ray spectrometry surveys allow determining a sub-circular structure roughly at 42°05´48´´S/68°40´43´W, slightly displaced by a NE-SW fault. This feature would complete the eastern border of the elliptic shaped caldera whose major and minor axes are 16 and 10 km, respectively.
b-The second and smaller caldera is located to the east of the previous one. It is circular, its diameter being approximately 7 km. Its center is occupied by a small pond referred to as *Laguna de los Flamencos*.
There are compositional differences between the products of both centres that can express their different ages and evolutionary stages. Related to the bigger caldera, lava domes and ignimbrites constitute a calc-alkaline sequence that is relatively older than the one corresponding to the *Laguna de los Flamencos Caldera.* The emissions of the latter caldera are lava flows and subordinate pyroclastic flows, with more alkalic affinities.
Session 1

Reinterpretation of deposits and eruption sequence of the Otowi Member, Bandelier Tuff Formation, Valles Caldera, Jemez Mountains, New Mexico

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The Otowi Member (1.6 Ma) produced Plinian and co-ignimbrite fall deposits, outflow and intra-caldera ignimbrite, and the first collapse event of Valles caldera (24 km diameter). Previous work shows eruption withdrew magma from a high-silica-rhyolite chamber possessing strong zonation in trace elements. Recent work reveals new insights on the products and eruption sequence: 1) The first phase produced Guaje fall deposit unit A, after which column collapse produced coeval pyroclastic flows and fall deposits (units B-F) in a complex depositional pattern. In places the ignimbrite is intra-Plinian and in others fall units could accumulate while pyroclastic flows by-passed the area. Combined physical and pumice composition data from deposits suggests that Plinian (vent-derived) fall deposition persisted late into the eruption. 2) The previous idea of switching from an initial central vent to vents on caldera ring-fractures at the time of deposition of co-ignimbrite lag-breccias is revised to reveal that the central vent persisted longer into the eruption on grounds of pumice composition combined with lithic abundances in ignimbrite. Lag-breccia deposition was thus not proximal to vent. 3) 50 km from vent, near Truchas, a preserved Otowi sequence shows fall units A-E and thin ignimbrite veneer; this shows that at least some of the pyroclastic flows were widespread and energetic and compositional data identifies these as some of the late-erupted flows. 4) A distal fall deposit extends > 600 km from source over Texas and consists of both Plinian column-derived and co-ignimbrite ash; ash composition is similar to lower units of Guaje fall deposit. 6) A revised minimum volume (DRE) estimate for Otowi deposits is: fall deposits > 100 km^3; outflow ignimbrite 140 km^3; intra-caldera ignimbrite 150 km^3; total ~ 390 km^3. The co-ignimbrite component of distal ash is almost certainly underestimated.
Session 3

DInSAR deformation analysis of summit calderas

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Summit calderas may deform as a consequence of several processes such as magma emplacement, flank instability, collapse and pressurization of a hydrothermal system. Modern remote sensing techniques, including DInSAR measurements, allow the detection of centimeter to millimeter scale deformation of a volcanic edifice and are invaluable tools for monitoring and understanding the relations between deformation and magmatic activity.
Here we analyze the deformation from 1992 to 2011 of three summit calderas retrieved by DInSAR data: Somma - Vesuvio, Etna and Tenerife.
The Somma is interpreted to be the preserved boundary of the calderas, still uncovered by volcanic products. A detail structural study of active faulting of the summit area, combined with DInSAR and levelling data, suggests that a relatively narrow sector of volcano spreads on its plastic sedimentary substratum. Spreading could control the formation of the "calderas", possibly influencing explosive volcanism and sector collapse.
Etna is a basaltic stratovolcano characterized by large deformation. The retrieved deformation patterns may be summarized as follows: from 1994 to 2000, the volcano inflates with a linear behavior accompanied by the eastward and westward slip on the E and W flanks, respectively. From 2000 to 2003, the deformation becomes non-linear, especially on the proximal E and W flanks, showing marked eastward and westward displacements, respectively; this is induced by the emplacement of feeder dikes during the 2001 and 2002-2003 eruptions. From 2003 to 2010, the deformation approaches linearity again. In addition, from 1992 to 2010 part of the volcano base has undergone a constant trend of uplift, of about 0.5 cm/yr.
Tenerife volcanic complex is affected by crustal deformation processes occurring at timescales of millions of years. Recently, space - based geodetic observations have also detected a short - term surface deformation, characterized by a broad subsidence pattern with velocities of about 4 mm / yr. An advanced fluid dynamic analysis show that the recent surface deformation is mainly caused by a progressive sagging of the denser core of the island onto the weaker lithosphere. Our study shows that a unitary physical model may explain both the deformation recorded in deep geological structures and the active ground deformation processes.
Session 5

The Diamante caldera – Maipo Volcano complex: a potential hazard in the central Andes (34° 10´S)

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The DCMV complex is located on the Andean border between Argentina and Chile (34° 10´S), within the northern section of the Southern Volcanic Zone, where the continental crust is ~55 km thick. In this segment, silicic volcanism, including multi-episodic calderas and large volume ignimbrites, is commonly recorded since late Pleistocene (Laguna del Maule Volcanic Complex, Calabozos Caldera, Quizapu Volcano, Río Colorado Caldera). In the DCMV complex two main stages may be distinguished: 1) the "Diamante stage" (150 ka) corresponds to the emplacement of large-volume (250 km^3) rhyolitic ignimbrites, which blanketed ~23,000 km^2 of Argentina and Chile and left a 10x16 km collapse caldera; this large-volume low-temperature (T<600º C) ignimbritic eruption could have been a short and catastrophic event with an estimated VEI of 7 and it records the biggest and most violent explosion that has taken place in the NSVZ in the last 200 ka; 2) the "Maipo stage" represents andesite-dacite stratocone-building lavas and pyroclastics emplaced during the last 100 ka of the complex lifetime. The eruptive record at Maipo consists of at least 4 pre-last glacial maximum events (~90-30 ka) and 3 post-glacial (<14 ka) small-volume events. Maipo volcano (5323 m) is a historically active stratovolcano nestled within the Diamante collapse caldera. At present, the two summit craters remain ice-covered, without fumarolic or hydrothermal activity. The last eruption tentatively occurred in 1912. The volcanics define a high-K, calc-alkaline suite ranging in silica from 54% to 74%. A general geochemical trend towards more evolved and potentially more explosive products is recognized. Understanding not only the volcanological and geochemical evolution of the DCMV complex, but the collapse mechanism as well are critical to hazard assessment.

Session 2

Caldera supervolcanoes, resurgence, and mineralization

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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 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 faults 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. Available evidence at Valles and Lake City calderas indicates that major pulses of hydrothermal activity are associated with and linked to caldera formation and resurgence, since resurgence immediately postdates collapse at both calderas. Based on these observations, we propose a mechanism for caldera-related hydrothermal systems and mineralization. Intermediate-composition, sulfur-rich magmas are introduced into the caldera system during collapse and resurgence. These magmas degas catastrophically as they rise and decompress, providing a source of magmatic-hydrothermal fluids which may be ore-bearing or barren. The intermediate magmas also supply a new source of heat with which to drive hydrothermal cells. Furthermore, the rising magmas cause deformation and fracturing to occur during resurgence, notably as inward-dipping reverse faults which are generated along the ring fracture of the caldera. The development of this fracture permeability is another key component allowing for a large hydrothermal system to develop rapidly. The permeability also provides pathways for meteoric fluids to circulate and interact with magmatic fluids. Notably at both calderas, the locations of the most intense hydrothermal activity (Sulphur Springs at Valles and Red Mountain at Lake City) are found along and around the calderas' ring fracture. As deformation and resurgence proceed, the inward-dipping reverse faults are progressively opened and filled with degassing magma and magmatic-hydrothermal fluids. These structures are akin to cone sheets and serve as repositories for magma, hydrothermal fluids, and potential ore minerals. These structural pathways are supplemented by other structures such as regional faults which cut through the caldera system. In summary, initiation of such hydrothermal systems is the result of heat, magmatic fluids, and fracture development from the intermediate magma which rises into the caldera system, interacts with resident magma, and drives resurgence. Hence the timing of caldera formation, resurgence, and hydrothermal activity is synchronous.

Session 5

What lithic-free eruptions tell us?

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Pyroclastic deposits from explosive eruptions of various magnitude and intensity usually contain a variable amount of lithic fragments from sedimentary and/or volcanic pile. Erosion processes during magma ascent, fragmentation and craterisation are responsible of the entrapment of lithic fragments into the eruptive mixture.

Nevertheless, lithic-free pyroclastic deposits (with less then 10 vol.%) sometimes occur from eruptions of various size and in different geological settings. The mechanisms responsible of this behaviour are still not understood, and probably rely on the interplay between magmatic overpressure and local stress.

Here we present three examples of lithic-free deposits from a violent strombolian/subplinian (AD 512; Somma-Vesuvius, Italy), a Plinian (Mercato, Somma-Vesuvius, Italy), and an ignimbrite forming (Zaragoza Ignimbrite; Los Humeros caldera, Mexico) eruption. The fall deposits from all of these eruptions contain between 5 and 10 vol. % of lithic fragments, although formed under very different mass discharge rates.

Session 3

On the long term non-Newtonian behaviour of resurgent calderas: The 1982-2010 Campi Flegrei (Southern Italy) case study

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Most of the volcanic deformation inverse modelling attempts to characterize the evolution of the volcanic sources over the assumption that the Earth's crust behaves as a homogeneous linear elastic material. However, the geological and geophysical information show that the behaviour of the upper lithosphere in thermally anomalous regions, as the case of active volcanoes, are strongly non linear both in space and time. In this context, we investigate the driving forces responsible of the long-term ground deformation of the Campi Flegrei (CF) caldera, Southern Italy, during the 1982-2010 time interval. To this purpose, we propose a new multiphysics numerical model that takes into account both the mechanical heterogeneities of the crust and the thermal conditions of geothermal system beneath the volcano. We perform a numerical Chain Rule Optimization Procedure (CROP) in FEM environment, that considers different physical contexts linked along a common evolution line: starting from the thermal proprieties and mechanical heterogeneities of the upper crust, we develop a 3D time dependent thermo-fluid dynamic model of CF caldera. More specifically, by carrying out two subsequent optimization procedures based on Genetic Algorithm, we search for the 3D distribution of unknown physical parameters (temperature and viscosity distributions) that might help explaining the data observed at surface (geothermal wells and DInSAR measurements).
The first step of the CROP approach allows retrieving the heat production and heat flux parameters providing the best-fit of the geothermal profiles data measured at seven boreholes, by solving the Fourier heat equation over time in conductive regime. The 3D thermal field resulting from this optimization is used to calculate the 3D brittle-ductile transition that represents the sub-domain setting for the subsequent fluid dynamic optimization.
In the numerical fluid dynamic context, we solve the Navier-Stokes equation over time, by using two different dataset: high precision levelling for the 1982-1985 time interval and DInSAR data acquired by ERS - 1/2 and ENVISAT sensors for the 1992-2010 time period.
The optimization results show that the stress accumulated during the 1982-1985 unrest phenomenon has been balanced by non-Newtonian properties of the crustal material inside the ductile region in 2005, when a new phase of background uplift is found. In terms of rheology, this new phase could represent a period of stress accumulation in the brittle region.

Session 5

Asymmetric caldera collapse: an example from Faial Island (Azores, Portugal)

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One of the main features of Faial island (Azores) is the caldera of the strato-volcano in the centre of the island. In order to reconstruct the caldera structure and its relationship with regional faults, we performed remote sensing and field analysis.
The subcircular caldera, formed 2 ka ago, is 2 km wide and 400 m deep. However, its slopes are asymmetric, with the inner southern slope being gentler than the northern one. The inner northern rim is characterized by a subvertical fault scarp, with a vertical displacement in the order of a few meters. The area south to the caldera is characterized by WNW-ESE trending regional fault systems with a clear morphological expression, partly connecting to the southern caldera rim. The deposits located between the faults south of the caldera rim and the southern morphologic caldera rim dip toward the caldera centre.
The overall structure of the caldera is therefore characterized by a marked structural asymmetry, with an inward tilted portion, controlled by regional faults, on the southern slope outside the rim. Hence, the caldera structural boundary continues outside the morphologic rim, reaching and reactivating the pre-existing regional structures trending WNW-ESE. Despite the subcircular depression, the caldera structure reveals an elliptical shape, with a major axis N45°E oriented, nearly parallel to the regional σ_3 direction.
Finally, the calculated caldera d/s ratio, that is 7, suggest that the caldera belongs to a mature evolution stage, with well-developed outer normal and inner reverse faults.
Session 1

Collapse, eruption and products of the crystal rich, >1000 km^3, Permian Ora ignimbrite and caldera super-eruption, Southern Alps, northern Italy

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Despite the large number of known modern and ancient calderas and their deposits, very few studies have documented the detailed facies characteristics of thick intra-caldera ignimbrite sequences and the associated eruption and depositional processes inside calderas. Studies of calderas and their deposits in the geologic record, provides valuable insights into magma forming processes, caldera eruption styles, timing of caldera collapse and transport and depositional processes of voluminous ignimbrites. This research is focused on the 277-274 Ma eruption of the Ora ignimbrite, Athesian Volcanic Group, Northern Italy, which produced one of the largest silicic Permian collapse caldera eruptions in Europe. This research is multidisciplinary in its approach incorporating fieldwork, AMS analysis, petrographic analysis and geochemistry.
At least 1000 km^3 of magma was erupted, from the volcano-tectonic system. The ignimbrite sheet spans approximately 1500km^2. The Ora ignimbrite is well preserved both in plan view and cross section. It is crystal rich (40-45%), lithic poor (<2%), ubiquitously welded, lacks a preceding plinian fallout deposit and preserves localised basal vitrophyre deposits. Although no obvious breaks have been found in the ignimbrite it is subtley stratified, involving variations in crystal size, abundance and sorting, and sharp depositional unit boundaries are lacking, suggesting caldera collapse, large volume ignimbrite eruption and aggradation of the 1.35 km thick intra-caldera ignimbrite pile occurred during a continuous, prolonged eruptive episode. The intra-caldera ignimbrite is up to 1.35 km thick and up to 230m in the outflow region, and comprises four main facies with sub-facies. Significant lateral differences have been discovered between the northern and southern collapse caldera regions, suggestive of two nested calderas with a complex multi-eruption point eruption process. These variations are revealed through differences in facies, non-uniform pyroclastic flow directions, reflected by AMS results and in total biotite contents, demonstrating clear variations across the preserved eruptive stratigraphy. The eruption is proposed to have begun with catastrophic roof failure, producing ‘boil-over’ eruption column dynamics with rapid column collapse events. Initial vent opening produced local lithic rich mesobreccia deposits and proximal lithic rich ignimbrite deposits, with the bulk of the ignimbrite deposit being lithic poor ignimbrite including low volume, discontinuous basal vitrophyre deposits. In addition to reconstructing the physical facies, stratigraphic and chemical architecture of the Ora ignimbrite and caldera we have also applied Anisotropy of Magnetic Susceptibility (AMS) to the intra-caldera ignimbrite, the first time this has been done, and perhaps also the oldest volcanic rocks to which AMS has been applied. This revealed that (i) a measureable AMS fabric exists, (ii) that AMS can be reliably applied to ancient, large volume intra-caldera ignimbrite deposits, providing understanding of broad temporal and lateral intra-caldera syn-depositional processes, shown to be heterogeneous, (iii) that AMS data can be used to clearly distinguish different depositional stages, supporting previous works that pyroclastic flows are dynamic and cause a meandering of flow directions along their flow path, and finally, (iv) that the AMS data can be used to help in the identification of eruptive source regions within caldera depressions.
The Ora Ignimbrite forms part of a major Permian ignimbrite flare up, like other large-scale crystal rich ignimbrite forming eruptions and their calderas, such as in the Andes.
Session 3

Relationships between the late Cenozoic caldera distribution, gravity and aeromagnetic data, in the NE Honshu arc, Japan

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In order to discuss the late Cenozoic caldera distribution and geotectonics beneath the NE Honshu arc, Japan, crustal structures deduced from gravity anomalies and aeromagnetic data are examined. We used a large gravity database recently published as CD-ROM (Yamamoto, Shichi and Kudo, 2011) and the aeromagnetic data published by the Geological Survey of Japan (Nakatsuka et al., 2005) for comparison with the late Cenozoic caldera distribution (Yoshida et al., 1999, Acocella et al., 2008).

Bouguer gravity anomaly distributions over the NE Honshu arc are characterized by NNE-SSW trend of steep horizontal gravity zones corresponding to the fault structures which were originated during Japan Sea opening. Short (less than 30 km) wavelength components of gravity undulations, which are many gravity depressions surrounded by steep horizontal gravity cliffs, are also dominant in this region. Kudo et al. (2010) reported that the distribution of the gravity depressions is strongly corresponding to the distribution of the late Cenozoic large calderas. Therefore, the density structure of these calderas might be a major factor of the gravity undulations of this region. Prima and Yoshida (2010) proposed an algorithm to delineate subsurface structural rims using gravity and aeromagnetic data. Considering that major calderas in the study area have significant regional depression on both data, a standard DEM (digital elevation model)-based hydrologic algorithm was conducted to each data to delineate subsurface structural rims showing subsurface caldera structures in the northeast Honshu. From both data, many existing calderas are identified. Although gravity data is likely superior to aeromagnetic data on identifying calderas, the aeromagnetic data detected some rims that unidentified by the gravity data.

Session 1