

### The Origin of Garnet Megacrysts in Sulu UHP Clinopyroxenite, East China

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Abundant garnet megacrysts occur in one garnet clinopyroxenite layer from Rizhao of the Sulu UHP terrane, east China. The clinopyroxenite layers with various contents of garnet (trace to > 40%), ilmenite (< 5%) and minor olivine form part of a strongly serpentinized peridotite body. Megacrystic Grt-bearing clinopyroxenite consists of variable amounts of megacrystic and porphyroblastic Grt, fine-grained matrix of Grt + Di + Ilm ± Ol (Fo<sub>82-85</sub>), and secondary Amp, Chl and Spl. The megacrystic Grt with ellipsoidal and spherical shapes ranges from 2.5 to 12 cm, are coated with Chl + Amp ± Cpx ± Ep ± Mt/Spl and develops distinct pressure shadow. Megacrystic Grt (Prp<sub>44-56</sub>Gr<sub>s21-41</sub>Alm<sub>18-26</sub>) has similar compositions to porphyroblastic Grt (Prp<sub>40-43</sub>Gr<sub>s37-40</sub>Alm<sub>20-21</sub>) but differs from matrix Grt (Prp<sub>25-32</sub>Gr<sub>s46-56</sub>Alm<sub>18-22</sub>). At some interfaces between Grt and Cpx, Grt contains Ca-rich and Mg-poor compositions (Prp<sub>23-25</sub>Gr<sub>s58-60</sub>Alm<sub>17-19</sub>). At least 6 types of inclusions occur: (a) trace spinel ± magnetite lamellae, (b) trace dolomite, (c) trace amphibole (3.0-3.4 wt% Na<sub>2</sub>O; 0.3-0.4 wt% K<sub>2</sub>O; 0.4-0.5 wt% TiO<sub>2</sub>), (d) ilmenite with magnetite lamellae and rare spinel, (e) abundant coarse-grained Cpx (0.5-1.0 wt% Na<sub>2</sub>O) with characteristic exsolution lamellae of Amp (0.4-1.3 wt% Na<sub>2</sub>O; 0.7-1.0 wt% K<sub>2</sub>O; Mg ~ 0.9; 0.1 - 0.2wt% TiO<sub>2</sub>) + Ilm ± Grt described by Zhang and Liou (2003), and (f) composite phases of Cpx (e) + Ilm + Amp with ilmenite exsolution lamellae. The Grt megacrysts are fractured and veined with amphibolite facies assemblage Amp + Spl + Cpx ± Pl and do not contain exsolved rutile needles. Available experimental data (4-15 GPa, 1000-1400°C) of an Ilm-rich garnet clinopyroxenite composition indicate that Grt coexisting with Cpx contains considerable amount of TiO<sub>2</sub> (> 1 wt%) only at P > 5 GPa; the results constrain the maximum depth for the formation of Grt megacryst. Parageneses and compositions of inclusion phases in megacrystic Grt and matrix minerals suggest the protolith of the megacrystic Grt-bearing clinopyroxenite probably was a high-Al clinopyroxenite formed at mantle wedge with an initial assemblage Cpx + Ilm + Spl ± Ol ± Dol at P < 3 GPa and T ~ 1200°C. Subsequent increase in P and decrease in T as the mantle fragment involved in a continental subduction zone, spinel reacted to form Grt whereas the Al-Ti bearing Cpx exsolved Amp + Grt + Ilm lamellae at subduction depths < 150 km. During exhumation and hydration, Grt coalesced to form megacrysts that engulfed relict lamellae-rich Cpx, Ilm, Spl, Amp and dolomite as inclusions. Porphyroblastic garnet formed subsequently and lamellae-rich Cpx recrystallized to matrix assemblage of Cpx + Grt + Ilm at ~800°C, ~3 GPa. Deformation at crustal depths fractured megacrysts and amphibolite facies recrystallization occurred.

### V12G MCC: 3006 Monday 1340h

#### Rift Zones on Volcanic Islands: Structure, Evolution, and Magmatic Processes I (joint with S, T)

**Presiding:** T R Walter, Rosenstiel

School of Marine and Atmospheric Science, University of Miami; A KLGEL, University of Bremen

### V12G-01 1340h INVITED

#### Effects of Mechanical Layering on Dike Emplacement, Faulting, and Surface Deformation in Rift Zones

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All rift zones in volcanic islands contain normal faults and dikes as their main structural elements. During rifting episodes there is normally fault slip, graben development and dike emplacement. Field and geodetic studies, however, show that most dikes emplaced in rift zones do not reach the surface but rather become arrested at certain crustal depths. Geodetic measurements of the surface deformation during rifting episodes are routinely used to model the depth to the tips, as well as the geometries, of arrested dikes. Most inverse models to infer the geometries of arrested dikes assume the rift zone to be a homogeneous, isotropic, elastic half space. All rift zones in volcanic islands, however, contain normal faults and other discontinuities, and consist of rock layers that often have contrasting mechanical properties, such as soft pyroclastic rocks and stiff basaltic lava flows. To explore the effects of mechanical layering on fault slip and dike emplacement during a rifting episode, many boundary-element models were run. In these models, the rift zone already has a graben, represented by two (boundary) normal faults, dipping at 70° toward the center of the rift zone. The rift zone is taken to be 10 km thick. In all the models the lower tips of the boundary faults are at the depth of 4 km below the surface; in some models the upper fault tips extend to a depth of 1.5 km below the surface, in others all the way to the surface. The rift zone is composed of alternating stiff (high Young's modulus) and soft (low Young's modulus) layers. In most models, the only loading is the internal magmatic overpressure that drives the dike. The first models indicate that the stresses generated by a dike propagating vertically up toward the bottom part of a graben tend to open up the boundary faults of the graben. However, when the upper tip of the dyke reaches the same crustal level as the bottom tips of the boundary faults, the magmatic overpressure associated with the dike forces the faults to close and subsequently, as the dike tip continues its propagation up into the graben, encourages reverse slip on these normal faults. The faults remain closed until the magmatic overpressure is relaxed. For the faults extending to the surface, the reverse slip generates a hoist. The second models show that soft layers and a weak contact at shallow depths suppress dike-tip tensile stresses and encourage dike arrest. Soft layers and a weak contact also suppress the surface stresses and deformation induced by arrested dikes and encourage transfer of the surface tensile stresses to the regions above the lateral ends of the weak contact. In these models, the tensile stress at the rift-zone surface in a large area above the arrested dike itself is very small, but rises above the lateral ends of the weak contact, many kilometers from the dike tip. Thus, for a dike arrested in a layered rift zone, straightforward inversion of surface-deformation data may yield geometric results that have little relation to the actual geometry of the arrested dike. The predictions of the numerical models are generally supported by field results from the volcanic rift zones of Tenerife (Canary Islands) and Iceland.

### V12G-02 1355h INVITED

#### Stresses Associated to the Onset of the Pu'u 'Ō'ō Kūpaianaha Eruption

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Ground deformation and seismicity are used in a complementary way in order to determine stressing processes before and at the onset of the Pu'u 'Ō'ō Kūpaianaha eruption. After the magnitude 7.2 Kalaupana earthquake and before the start of the ongoing eruption in 1983, deformation of Kilauea volcano was the most rapid ever recorded. Modeling shows that this deformation was characterized by the dilation of a dike-like magma system within Kilauea's rift-zones, coupled with aseismic creep over a narrow zone of a low-angle fault located beneath the volcano's south flank. For the 1976-1983 period, rates of rift zone opening averaged 40 centimeters a year resulting in a magma supply of 0.19 cubic-kilometer per year. The onset of the Pu'u 'Ō'ō Kūpaianaha eruption was associated with a 2.1 meter fissure opening in the east rift-zone and a significant change of the south-flank seismicity pattern and rates. Coulomb stresses associated to the fissure opening are computed using a three-dimensional boundary element method for two different models that fit the deformation data equally well - a model in which the inflating rift dike propagated from a depth of 3 km to the free surface, and a model of an isolated intrusion of a shallow dike. Then, Coulomb stresses are computed independently from earthquake rates using a newly developed method [Dieterich *et al.*, 2000]. We find that the Coulomb stresses determined from seismicity agree with the model corresponding to the propagation of the rift dike to the surface. Moreover this model is mechanically consistent with our model for the 1976-1983 period.

### V12G-03 1410h INVITED

#### Simultaneous Submarine and Subaerial Volcanic Activity on the Flanks of the Western Canary Islands La Palma and El Hierro

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The westernmost and youngest Canary Islands La Palma (2.0 Ma) and El Hierro (1.1 Ma) are presently in their shield stages. The subaerial and submarine morphology of both islands is characterized by one or three elongated ridges, respectively, commonly interpreted as volcanic rift zones. Our investigations indicate that young submarine volcanic activity off the islands is not confined to the extensions of these rift zones, but is also dispersed along the island flanks. Fresh basaltic rocks dredged along these flanks (RV "Poseidon" cruise 270 in 2001, and RV "Meteor" cruise M43 in 1998) comprise basanites to tephrites and alkali basalts. Remarkably, the dredged lavas are geochemically more diverse than those of the Holocene subaerial ridges. Fresh basalts have been recovered from 21 young volcanoes on the submarine flanks of El Hierro at depths from 800 to 2300 m. Another 25 volcanic cones can be tentatively identified from morphologies similar to the dredged ones. These submarine volcanoes off El Hierro occur in a dispersed manner on the blunt noses representing the extensions of the postulated subaerial northeast and northwest rift zones but also off the rift axes. Young volcanoes also occur within the Las Playas and El Julian landslide scars, testifying to renewed volcanic activity following large landslides. On the east flank of La Palma, we recovered basaltic rocks from 8 volcanic cones at depths between 850 and 2200 m and at a distance of up to 30 km off the rift axis, recognizing another 20 possible volcanoes in the same area from high-resolution bathymetric data. Remarkably, young submarine volcanoes are comparatively rare on the western flank and the submarine extension of the Cumbre Vieja rift zone. The high density of apparently young volcanoes on the NE and NW slopes of El Hierro suggests that submarine volcanism is volumetrically important during subaerial growth stages of the Canary Islands. Our results indicate that a broad melting anomaly involving distinct sources must occur in the mantle beneath La Palma and El Hierro.

## V12G-04 1425h

## Diffuse Rift Zones: Subaerial and Submarine Satellite Vents at Wolf Volcano, Galapagos

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Wolf Volcano is one of the type-locality Galapagos shields, characterized by steep upper slopes, circumferential fissures near the summit, and a large and deep caldera. Fissures on the flanks of the volcano are radially distributed. Although the radial vents are concentrated in the northwest, northeast, and southern sectors of the volcano, the individual fissures are not aligned in sharp rift zones. Our preferred interpretation is that instead of being classic volcanic rifts, sectors of the volcano are absent vents, owing to gravitational stresses exerted by the caldera walls, neighboring volcanoes, and unusually steep slopes. The lack of vents in these areas concentrates vents in other sectors of the volcano. In contrast, bathymetry and sidescan sonar reveal that submarine Wolf has two volcanic rifts, one to the northwest and another that extends to Roca Redonda volcano. These submarine rifts are marked by linear alignments of vents and fissures and have produced young unconsolidated lava. The submarine lavas are compositionally identical to those erupted from the subaerial part of the volcano, indicating that they intrude laterally from the subcaldera magma chamber. All of the lavas erupted from the volcano are similar in composition, indicating thermal and chemical buffering of the magma in a well-mixed, steady-state system. Wolf lavas are unusual in that their isotopic composition is indistinguishable from that of depleted MORB erupted from the nearby Galapagos Spreading Center. Their trace element concentrations, however, are nearly that of E-MORB. Thus, we believe that Wolf magmas are produced by low degrees of melting of nearly pure asthenosphere, either from the margins of or entrained within the Galapagos plume.

## V12G-05 1440h

## Magmatic Consequences of Failed Rift Zones: Examples from the Eastern Pacific

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The aseismic Cocos Ridge, one of the most prominent bathymetric features in the eastern Pacific, records 20 million years of interaction between the Galapagos hotspot and the Galapagos Spreading Center. Two major clusters of seamounts are located along the northern flanks of the ridge, one near the Costa Rican coast and the second around Cocos Island. The Costa Rica and Cocos Seamount Provinces (including Cocos Island) have produced alkalic lavas accompanied by enrichment in incompatible trace elements beyond any observed in the Galapagos Archipelago today or in samples from the crest of the Cocos Ridge. Cocos Island is known to be millions of years younger than the hotspot track on which it lies, and the other seamounts likely share this characteristic. Trace element data determined by ICP-MS from over 90 dredged samples from the ridge and seamounts suggest that the compositions of the lavas are strongly controlled by the history of rift jumping in the region. The lavas are the result of small degrees of melting of a Galapagos plume-like source, predominantly in the garnet stability field. In the case of both seamount fields, their eruption immediately follows the failure of a rift zone at each province's location. Thus we attribute the anomalously young alkalic lavas of the seamount provinces to post-abandonment volcanism following either a ridge jump or rift failure, and not to the direct activity of the Galapagos plume. The seamounts and Cocos Island are instead the result of passive upwelling caused by a major tectonic rearrangement, such that the seamounts are significantly younger than their supporting lithosphere or the hotspot trace. The failed

rift tapped mantle that had previously incorporated Galapagos plume material when the lithosphere was produced at the plume-affected GSC. Fundamentally, the hotspot's variable interaction with the Galapagos Spreading Center, coupled with rift failures associated with tectonic rearrangements of the ridge itself may be the dominant factors in controlling regional magmatism and may be responsible for the formation of some enigmatic oceanic volcanoes such as Cocos Island.

## V12G-06 1455h

## A Comparison of two Northeastern Atlantic Rift Systems With Hawaiian Rift Systems

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Models on magma transport within and beneath rift zones are largely based on Hawaiian volcanoes and are not necessarily transferable to other oceanic islands. We carried out comparative studies on the active Cumbre Vieja rift zone of La Palma (Canary Islands) and on the fossil Madeira and Desertas rift systems (Madeira Archipelago) representing shield stage volcanoes at hotspots less productive than the Hawaiian. Different barometers were used to constrain magma pathways beneath the Madeira and La Palma rift systems and to compare the results with models for Hawaiian rift zones. Pressures obtained by cpx-melt barometry are interpreted to reflect major fractionation levels and generally indicate depth ranges within the uppermost mantle: 16-27 km for Cumbre Vieja, 15-32 km for Madeira and 16-28 km for Desertas. In contrast, microthermometry of CO<sub>2</sub>-rich fluid inclusions yields pressures within the lowermost crust to uppermost mantle (Cumbre Vieja: 7-14 km, Madeira: 8-10 km, Desertas: 9-17 km) that are interpreted as temporary stagnation levels. Further stagnation within the upper crust that may reflect shallow rift pathways was only found for the Desertas rift at 2-4 km depth. Our models of the magma plumbing systems beneath La Palma, Madeira and Desertas are thus characterized by (i) major fractionation levels in the upper mantle, (ii) temporary stagnation levels in the lower crust to the Moho, and (iii) local rift pathways. In none of the investigated volcanoes there are any indicators of a high-level magma reservoir feeding the rift zones. This is an important difference to models for Hawaiian rift zones characterized by shallow subcaldera magma chambers from where rift zones emanate. For Hawaii there is also evidence for prior magma storage and fractionation near the mantle/crust boundary and within the upper mantle, similar to the situation at the Atlantic rift systems studied. The lack of long-lived shallow magma chambers at La Palma and Madeira is best explained by their lower eruption rates as compared to Hawaii and the lower buoyancy fluxes of the respective mantle plumes.

## V12G-07 1510h

## Magma inflow into Katla, one of Iceland's most hazardous volcanoes

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Katla is one of Iceland's most active volcanoes, with twenty large eruptions in the last 1100 years. A seismic survey suggests the presence of a magma chamber under the volcano at 4-5 km depth. The volcano is ice-capped, thus making Katla eruptions phreatomagmatic and capable of triggering jokulhlaups. A minor jokulhlaup in July 1999 associated with an episode of continuous seismic tremor was probably the first sign of resumed magmatic activity under the volcano. GPS measurements on nunataks at the rim of the subglacial caldera, have revealed steady inflation due to magma accumulation from 1999 onwards. These measurements show uplift and horizontal displacement of the nunatak stations at a rate of up to 2 cm/yr, and horizontal displacement of the far field stations at about 0.5 cm/yr

away from the caldera centre. Findings suggest progressive caldera inflation over time. Inflation was modeled with a point-source, giving an uplift rate of about 2 cm/yr since 2000. Recent magma inflation falls below the volume of that previously extruded in 1918. The agitated state of the Katla volcano is further expressed by increased earthquake activity that has remained abnormally high and continuous since 2001. Historic Katla eruptions have initially been explosive, allowing high rates of enthalpy extraction due to profuse melting of the glacier base. Floodwater gathers rapidly in a large and inherently unstable water reservoir that bursts suddenly to produce a cataclysmic jokulhlaup that peaks within a few hours. The proximity of the Katla volcano to populated areas and international flight paths makes this volcano one of Iceland's most potent geological hazards.

## V12G-08 1525h

## Magma-tectonic interaction at Mauna Loa, Hawaii: Earthquake stress change influence on direction of dike propagation at rift zones

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There is ample evidence for earthquake volcano interaction at Mauna Loa. An M 6.6 earthquake at the eastern flank of the volcano preceded the 1984 eruption. An M 6.3 earthquake at the western flank preceded the 1950 eruption. An M 7.0 earthquake at the southeastern flank of Mauna Loa preceded the 1868 eruption. Earthquake focal mechanisms suggest a cause by gravitational spreading and fault slip near the base of Mauna Loa. The eruptions that followed initiated at the summit caldera, from where the fissures propagated along the northeast rift zone NERZ (1984) or along the southwest rift zone SWRZ (1868, 1950). Using three-dimensional boundary element models we calculate stress changes associated with earthquakes larger than magnitude 6. The earthquakes caused a decrease of Coulomb stress at the magma chamber, probably triggering the eruption. Moreover, the patterns of extensional normal stress for the rift zones coincide with the locations of the eruptive fissures (SWRZ or NERZ) at Mauna Loa. This suggests that the propagation of dikes is controlled by the change in stress related to gravitational spreading earthquakes.

## V12H MCC: 3008 Monday 1600h

## Volcanic Emissions to the Troposphere: Budgets, Sources and Impacts (joint with A, B)

Presiding: D Pyle, Cambridge

University; C ( de Hoog, University of Gothenburg

## V12H-01 1600h INVITED

## Volatile Emissions from Subduction-related Volcanoes: Major and Trace Elements

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Present-day volatile emissions associated with subduction zone volcanism can be estimated in two ways. One approach is to assume magma production rate at arcs is 20% that of MOR and scale to the MOR <sup>3</sup>He flux (1000 mol/yr) to obtain a mantle-derived arc He-3 flux of 200±40 mol/yr. This flux and measured gas ratios ( $x_f$ /<sup>3</sup>He is the gas species of interest) obtained from volcanic and hydrothermal samples is then used to calculate volatile emissions. A global arc CO<sub>2</sub> flux of 0.3 to 3.1 x 10<sup>12</sup> mol/yr has been obtained in this way. Another approach is to use individual arc volcano SO<sub>2</sub> fluxes (determined by remote sensing) in combination with CO<sub>2</sub>/SO<sub>2</sub> ratios of high temperature fumaroles to calculate volcanic CO<sub>2</sub> fluxes. Integrating over an individual arc, and using a power-law distribution to include non-measured volcanoes, it is possible to produce a volatile flux estimate for a particular arc. Summing over all arcs allows a global estimate (e.g. ~ 1.6 x 10<sup>12</sup> mol/yr for arc CO<sub>2</sub>).