

R/V SONNE 208 PLUMEFLUX Cruise: Extent of the influence of the Galapagos Plume on the surrounding upper mantle and variations in plume-ridge interaction through time

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The R/V SONNE cruise (funded by the German Ministry for Education and Research) had two major study areas. During Leg 1, nineteen seamounts on the Cocos Plate, formed at the East Pacific Rise but presently located off the coast of NW Costa Rica and SW of Nicaragua, were sampled to evaluate: 1) if they were formed by the Galapagos hotspot and thus to constrain the extent of the influence of the Galapagos plume on the upper asthenosphere and lithosphere, and 2) to constrain better the input into the Central American subduction zone. The second study area was the Cocos-Nazca (Galapagos) Spreading Center (GSC) north of the Galapagos Hotspot. The main goal of Leg 2 was to sample profiles of the seafloor perpendicular to the GSC, in order to reconstruct plume-ridge interaction in the past. We mapped (with Simrad EM-120) and collected samples via dredging from 60 localities along five profiles. The first and most detailed profile (with 23 sampled localities) extended from the ridge axis at $\sim 92^\circ\text{W}$, where the R/V Atlantis AT15-63 GRUVEE cruise carried out a detailed sampling with Alvin of the ridge axis earlier in the year, to ~ 50 km to the north. The ridge-flank morphology shows alternating regions of abyssal hills (possibly reflecting less plume input into the ridge) and wider bands of elevated topography commonly containing seamounts, some of which are tectonically deformed (possibly reflecting axial ridge type morphology and thus greater plume input into the ridge). The second profile was carried out at the shallowest part of the ridge axis, closest to the hotspot, just to the east of the 91°W Transform fault. The profile was kept to 15 km, because further north the Cocos Ridge begins, which was extensively sampled during the R/V Melville MV1007 cruise in June 2010. The third profile extended 30 km north of the ridge at $\sim 89.50^\circ\text{W}$, where a seamount has been split across the spreading ridge. We want to evaluate how far in the past the unique enriched geochemical anomaly associated with the seamount persisted. Thirteen sites were successfully sampled along a fourth profile at $89^\circ 10'\text{W}$, extending 35 km north and 35 km south of the spreading center into crust up to 500,000 yrs old. This site was selected, because a major depleted geochemical anomaly coincides with a left-lateral en echelon offset of the ridge axis, possibly forming an incipient overlapping spreading center. A final short profile was carried out to the north and south and east (on the ridge axis) of a lava plateau at $88^\circ 20'\text{W}$ that fills in valley and ridge type morphology on the ridge and represents an enriched anomaly along the ridge axis. Seafloor morphology strongly suggests that the intensity of interaction of the plume with the ridge has varied considerably over the last several hundred thousand years along the entire part of the ridge that we studied. Geochemical data should allow us to constrain better variations in plume-ridge interaction through time.

¹ Werner, R. et al., 2010. R/V SONNE 208 PLUMEFLUX Cruise: Extent of the influence of the Galapagos Plume on the surrounding upper mantle and variations in plume-ridge interaction through time, AGU Fall Meeting. EOS, San Francisco, USA

Basaltic Diatreme To Root Zone Volcanic Processes In Tuzo Kimberlite Pipe (Gahcho Kué Kimberlite Field, NWT, Canada)

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Tuzo pipe is infilled by a series of coherent and fragmental kimberlite facies types typical for a diatreme to root zone transition level. Coherent or transitional coherent kimberlite facies dominate at depth, but also occur at shallow levels, either as dikes or as individual or agglutinated coherent kimberlite clasts (CKC). Several fragmental kimberlite varieties fill the central and shallow portions of the pipe. The definition, geometry and extent of the geological units are complex and are controlled by vertical elements.

Specific for Tuzo is: (1) high abundance of locally derived xenoliths (granitoids and minor diabase) between and within the kimberlite phases, varying in size from sub-millimeter to several tens of meters, frequent in a belt-like domain between 120-200 m depth in the pipe; (2) the general presence of CKC, represented by round-subround, irregular to amoeboid-shaped clasts with a macrocrystic or aphanitic texture, mainly derived from fragmentation of erupting magma and less commonly from previously solidified kimberlite, as well as recycled pyroclasts. In addition, some CKC are interpreted to be intersections of a complex dike network. This diversity attests formation by various volcanic processes, extending from intrusive to explosive; (3) the presence of bedded polymict wall-rock and kimberlite breccia occurring mostly in deep levels of the pipe below 345 m depth. The gradational contact relationships of these deposits with the surrounding kimberlite rocks and their location suggest that they formed *in situ*.

The emplacement of Tuzo pipe involved repetitive volcanic explosions alternating with periods of relative quiescence causing at least partial consolidation of some facies. The volume deficit in the diatreme-root zone after each eruption was compensated by gravitational collapse of overlying diatreme tephra and pre-fragmented wall-rock xenoliths. Highly explosive phases were alternating with weak explosions or intrusive phases, suggesting an external factor to control the explosive behaviour of the magma. The overall constant volatile content of the kimberlite does not explain the observed extreme change in emplacement behaviour. The facies architecture of fragmental facies dominated by vertical elements is similar to that in non-kimberlitic diatremes and indicates deposition from debris jets marking separate and repeated explosive volcanic events. In basaltic pipes, such jets are generated by phreatomagmatic explosions in the explosion chamber(s) of the root zone, causing abundant country rock fragmentation and further efficient mixture of the various particles.

Phases of high explosivity formed the finely fragmented kimberlites containing a high percentage of wall-rock xenoliths, while the fluidal-shaped and partly welded texturally variable and wall-rock-poor transitional coherent facies suggest phases of repetitive, hot, and low-energy fragmentation forming kimberlite spatter. Peperite hosted in kimberlite tephra is also typically found in basaltic root zones. Time

gaps in between volcanic eruptive periods are indicated by cognate pyroclasts and reworked wall-rock deposits emplaced by sporadic sedimentation events in subterranean cavities under the widening roof of the pipe. The presence of temporary caves in the root zone is proposed also by the occurrence of spherical CKC in deep-seated fragmental kimberlite and by spatter found in transitional coherent rocks. Evidence for caves was mostly preserved at deeper pipe levels advocating continuously recurring processes during the life span of Tuzo.

Seghedi, I., Kurszlaukis, S. and Maicher, D., 2009. Basaltic Diatreme To Root Zone Volcanic Processes In Tuzo Kimberlite Pipe (Gahcho Kué Kimberlite Field, NWT, Canada), AGU Spring Meeting Joint Assembly, Toronto, Canada, V24A-02.

Mineralogy of the “digested” wall-rock xenoliths in the transitional coherent facies of Tuzo diatreme (Gahcho Kué cluster)

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Transitional facies “Hypabyssal kimberlite” (HKt) in Tuzo diatreme is an aggregation of sub-horizontal texturally variable coherent kimberlite clasts that have different groundmass composition and crystallinity. HKt occurs mostly towards the bottom of the diatreme (18-24 m at >240 m below surface), rarely in the upper part (1.5-5 m). The clasts are composed by olivine macrocrysts and phenocrysts usually altered to serpentine; the groundmass includes variously sized poikilitic phlogopite, equally distributed spinel and perovskite, apatite next to deuteric serpentine, sulphides and carbonates. Randomly distributed 5-20% wall-rock xenoliths (various Archean granitoids and diabase), from less than one mm to several cm are also included; the mm size xenoliths are totally digested while the larger ones are partially digested. The proof for the clast digestion is their remnant shape and relict mineralogy and totally dissimilar new mineralogical assemblage. From rim to core using Cameca microprobe apatite, clinopyroxene, fluor-phlogopite, amphibole (zoned fluor-richterite with arfvedsonite rims) are present. Some amphibole crystals are unusual large growing toward the core, where are bordered by unidentified fine-fibrous silicate. We envision that wall-rock clasts reached high temperature quickly and then recrystallized. Carbonate and serpentine minerals are secondary.

Clastogenic texture of HKt and strong chemical disequilibrium of digested wall-rock clast are typical features of the diatreme. Highly gas-charged fluidized silicate melt forming a tough, and compact rock assemblage via agglutination, welding, lithification by cooling, and possibly vapour phase crystallization suggest a temporarily open space in the diatreme. This is in agreement with experimental studies (see Czamanske & Atkin, 1985 and references therein), that agree with low pressure (less than 0.1 GPa) and high temperature for alkali amphiboles generation.

[1] Czamanske & Atkin (1985) *Am. Mineral.* **70**, 499-516.

ⁱⁱ Seghedi, I., Ntaflos, T., Kurszlaukis, S. and Maicher, D. (2009) Mineralogy of the “digested” wall-rock xenoliths in the transitional coherent facies of Tuzo diatreme (Gahcho Kué cluster), Goldschmidt Conference, Davos, Switzerland, pp. A1190

An alternative interpretation of transition zones in kimberlite pipes

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Keywords: kimberlite, pipe, transition zone.

Exploration and mining activity of kimberlite pipes allows access to rocks in the root zones of maar-diatreme pipes. In some cases, these root zones comprise a sequence of rock types which has been reported from several kimberlite root zones from different locations but which appears to be specific to kimberlites. However, the rock sequence allows us to draw conclusions on the emplacement behaviour of kimberlite maar-diatreme volcanoes and is therefore of interest in both a volcanological and economic perspective.

The rock sequence encountered in these root zones spans from coherent magmatic rocks to fragmental volcanoclastic rocks with transitional rock types in between (Hetman et al., 2004; Skinner and Marsh, 2004, 2006; Seghedi et al., 2008). The coherent magmatic end member occurs at depth and is conventionally called “Hypabyssal Kimberlite” (HK). These rocks are comparable to HKs found in the (feeder) dyke system of a pipe. The volcanoclastic end member occurs in higher levels of the pipe and is a rock type which is often called “Tuffisitic Kimberlite” (TK). It is also rather specific to kimberlite diatremes and is characterized by a particular matrix mineralization and type of pyroclast as well as its structure and texture. Transitional rock types occur in between these end members and are subdivided into transitional HK (“HKt” - if the overall character of the rock is rather coherent and closer to HK) and transitional TK (“TKt” – if the character is dominantly fragmental in nature, but still has some features typical for coherent rocks). None of the rock types contains vesicles that would be indicative of exsolution of a juvenile gas phase.

A typical feature of transition zones is the gradual contact between the rock types. Differences in the texture of rocks are difficult to define and the gradual contact between rock types may span over several meters, sometimes even tens of meters. Some contacts also show an oscillation of rock types, where they alternate gradually on a relatively small scale (a few meters) until finally one rock type dominates.

It should be noted that the potential influence of post-emplacement mineral growth on primary textures by hydrothermal alteration is not well understood. This process is a further complicating factor as textural differences in kimberlite transition zones are often very subtle. More robust indicators for determining the different rock types are increasing abundances of country rock xenoliths towards fragmental rock types and changes in diamond grade.

Transition zones in kimberlite pipes were interpreted in several ways in the past. One interpretation ascribes transition zones as a flash frozen fluidization front earlier moving downward in the pipe while fragmenting and fluidizing a pre-breakthrough, gas-charged embryonic pipe consisting originally of coherent kimberlite (e.g. Hetman et al., 2004). In this model the HK at depth of the transition zone is seen as the gas-poor, unfluidized portion of this embryonic pipe. Since the entire pipe is supposed to have formed in one major eruptive event, the

diamond population and also the chemistry of the rock types should be identical throughout the pipe.

Another interpretation of transition zones suggests a major, pipe-forming (Plinian) eruptive event(s) as a consequence of expanding gas phases (Sparks et al., 2006; Cas et al., 2008). These eruptions excavate the crater down to the root zone, i.e. down to a depth of up to 2.5 km in the case of kimberlites. During peak eruptive activity, the entire deep crater is filled with a rapidly expanding low density gas-magma-solid particle stream. In this model the transition zone rocks are a consequence of welding processes of a large volume of hot tephra which is deposited in the waning phase of the eruptive event. This model implies that the root zone at one stage was actually a temporary and short-lived crater floor. Due to the high production rate in a Plinian eruption and the rapid sedimentation of tephra at the end of the main eruption, diamond characteristics and the chemistry of the rock types within the transition zone should be comparable.

While both of the previous models work with the expansion of gas phases as pipe forming events, the phreatomagmatic model uses the conversion of thermal energy into kinetic energy to fragment country rocks and the expansion of water vapor as well as juvenile gas phases to eject the pyroclastic material (Lorenz and Kurszlaukis, 2007). The process works best at optimal magma-water ratios and with large interactive surfaces between magma and water. If the conditions are not optimal, for example if not enough water has access to the explosion chambers in the root zone, then magma can intrude as a coherent body into levels of previous fragmentation and forms dykes, sills and plugs in the root zone or even in high levels of the pipe. A further major difference to the above models is that in the phreatomagmatic model the emplacement of a pipe may occur over time, possibly weeks or months (or longer?) and that different magma batches can be involved. Furthermore, because the work of expanding juvenile gas phases is not required to explain pipe forming processes, the absence of vesicles in transition zones is not a stumbling block to explain the emplacement of the pipe; juvenile gas phases may either be already or not yet exsolved.

As examples of transition zones in root zones we use the 5034 and Tuzo pipes in the Gahcho Kue kimberlite field, Northwest Territories, Canada. Both pipes show a typical transgression from HK at depth to TK in shallower levels, with HKt and TKt rocks defining the transition zones (Hetman et al., 2004; Kurszlaukis and Lorenz, 2008; Seghedi et al., 2008). The 5034 transition zone is generally xenolith poor and shows only a minor increase of xenoliths towards the fragmental rock types. However, the diamond grade varies throughout the drill core samples.

In contrast, the TKs in Tuzo can show extremely high abundances of dilution. The HKs at depth, conversely, are almost xenolith free. Tuzo drill cores also show domains of coherent kimberlite hosted in fragmental rocks, which range from a few cm to several meters in size. We interpret at least some of these domains as peperites, a complex dendritic network of dykes intruding pre-existing tephra. There is also evidence that welding of tephra played a role during emplacement and that some of the larger domains are actually welded tephra layers. It has to be noted that welding is seen to have occurred locally within temporary cavities within the root zone and is not a product of a collapsing Plinian eruption column filling a very deep crater.

Whole rock chemistry analysis of samples taken in regular intervals down the cores suggests that the HKs from both pipes are different in composition compared to the overlying transitional and fragmental rocks. In addition, the HK in

one of the lobes in 5034 shows evidence of two separate HK batches, which are petrographically not distinguishable, but explain a pronounced change in diamond grade within the HK.

In conclusion, our data does not support an origin of transition zone rocks from only one major eruptive event, either from a downward migrating fluidization front of a pre-existing embryonic pipe, or a deep crater/diatreme filling by a collapsing massive eruption cloud. Instead, we suggest that the transition is the expression of a highly altered interface of late HK magma intruding into the base of a pipe filled already with loose and still hot tephra. The heat of the intruding kimberlite will lead to sintering and compaction of tephra along the contact between the coherent and fragmental rocks. A very hot hydrothermal system (epi- to mesothermal) is established which will lead to the crystallization of specific mineral assemblages as the system cools down, and prevent others to crystallize. The interface itself will be complex, and smaller kimberlite bodies will intrude the overlying tephra as sheets and form a complex peperite system with local explosions creating short-lived cavities. This scenario explains the observed differences in textures, xenolith content, chemistry and diamond content.

Acknowledgements

The authors want to thank De Beers Consolidated Mines and Mountain Province Inc. for permission to publish data on Gahcho Kue kimberlites.

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Volcanology of Tuzo pipe (Gahcho Kué cluster) - root-diatreme processes re-interpreted

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The Middle Cambrian (~540 Ma) Gahcho Kué Kimberlite Field is situated about 275km ENE of Yellowknife, NWT, Canada. The Field is emplaced into 2.6Ga Archaean granitic rocks of the Yellowknife Supergroup. Four larger kimberlite bodies (5034, Tesla, Tuzo, and Hearne) as well as a number of smaller pipes and associated sheets occur in the field.

In plan view Tuzo pipe has a circular outline at surface and widens towards depth. In winter 2007 Tuzo was drilled in a 35m-spacing grid of 26 vertical HQ drill cores to a depth of 300 or 400m. This study presents our volcanological key observations and suggests a new emplacement mechanism, which varies from the conventional processes suggested up to now for the Gahcho Kué pipes.

The pipe infill consists of several types of coherent and fragmental kimberlite facies. While coherent or apparent coherent (possibly welded) kimberlite phases dominate at depth, the central and shallower portions of the pipe are comprised of fragmental kimberlite varieties, which are texturally classified as Tuffisitic Kimberlites. Several transitional kimberlite facies are recognized, which usually have gradual contacts to the adjacent kimberlite units. The definition and extent of the geological units is complex, and vertical elements seem to dominate over a significant lateral extension. Although coherent hypabyssal kimberlite (HK) dominates at depth, some HK intersections occur at shallow levels. They either represent late dykes or individual coherent magma particles (CMP). At least some of the CMP are the product of magma disruption in a semi-plastic state or even of welded material, as indicated by their fluidal outline and internal grain-aligned texture.

Steeply bedded epiclastic grain flows occur in deep levels of the pipe and especially under the downwards widening roof segments. The gradual contact relationships of these deposits with the surrounding kimberlite rocks as well as their location suggest an *in situ* origin.

Within and in between the kimberlite phases a variable and often high abundance of local country rock xenoliths is observed, varying in size from sub-mm to several tens of meters. Country rock fragments can be found in any location within the pipe, but are especially pervasive in a belt-like area at a depth of 120-200 m and under the widening roof. The texture and structure of the breccias propose an origin as contact breccias, slump breccias, grain flows, rock fall or pyroclastic deposits.

The shape and facies architecture in the Tuzo pipe suggests a root zone-diatreme transitional structural level. Composite juvenile pyroclasts imply that

recycling processes were active over time, while *in situ* grain flows and softly-deformed clasts of welded kimberlite point towards the presence of temporary caves in the root zone. It is clear from our study that the emplacement of the Tuzo pipe did not occur in a single, violent explosion, but that repetitive phases of volcanic explosions alternated with periods of relative quiescence. The observed volcanological features are typical of those expected in the thermohydraulic process chain, which may include minor phases of less-explosive magmatic activity.

Seghedi, I., Maicher, D. and Kurszlaukis, S. (2008) Volcanology of Tuzo pipe (Gahcho Kué cluster) — Root-diatreme processes re-interpreted, 9th International Kimberlite Conference, Frankfurt, Germany; A-00053.

WHOLE ROCK CHEMISTRY INVESTIGATIONS OF THE 5034 AND TUZO KIMBERLITES AND POTENTIAL APPLICATIONS TO IMPROVING GEOLOGY AND RESOURCE MODELS, GAHCHO KUÉ PROJECT, NORTHWEST TERRITORIES

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The Gahcho Kué Project is an advanced diamond evaluation project in joint venture with Mountain Province Diamonds Inc., located about 300 km northeast of Yellowknife in the Northwest Territories. The Gahcho Kué kimberlite cluster is comprised of the Hearne, 5034, Tuzo and Tesla pipes. New petrographic textural models were developed after core drilling programs were conducted at two of the four main lobes comprising the 5034 kimberlite, the North and East Lobes in 2006-2007, and at the Tuzo kimberlite in 2007. The two other main 5034 kimberlite lobes, the West and Centre Lobes, do not have detailed internal geology models. Both the 5034 and the Tuzo kimberlites have similar major textural kimberlite facies recognized: coherent rocks (distinguishing xenocrysts-macrocrysts, phenocrysts and groundmass minerals) comprising Hypabyssal Kimberlite (HK) and transitional Hypabyssal Kimberlite (HKt), and fragmental rocks (distinguishing framework components – magmatic or xenolithic or cognate-autolithic origin and matrix) comprising Tuffisitic Kimberlite (TK) and transitional Tuffisitic Kimberlite (TKt).

Whole Rock Chemistry (WRC) investigations were conducted to determine if it was possible to improve confidence in the 5034 and Tuzo geology models and support understanding of their diamond distributions in terms of the major rock types. Whole rock samples from the 5034 kimberlite underwent Principal Component Analysis conducted on major and trace elements using JMP® 7.01 Statistical Discovery™. For the Tuzo data set, major and trace elements including REE were variously compared in binary, ternary and trivariate plots and in Spider diagrams. At Tuzo the geochemical signature of the lithologies is strongly influenced by the variable and generally high degree of country rock contamination, with granitic material the most significant chemical contaminant.

The WRC studies provide an opportunity to improve understanding of major rock types and their diamond distributions at 5034 and Tuzo. At the 5034 kimberlite, WRC Principal Component Analysis has supported petrological observations and identified similar HK and HKt units across the four major lobes, with the HK and HKt being geochemically distinct within lobes; TKt and TK units being geochemically distinct between lobes and having variable overlap with HKt units; and two geochemically distinct HK's being evident within the 5034 Centre Lobe which reflect a change in large diameter drill bulk sample diamond grades. It is recommended that a more detailed investigation of the 5034 West and Centre

Lobes is undertaken to delineate the major rock types and to increase confidence in the geology model.

At the Tuzo kimberlite, preliminary WRC investigations indicate that there appears to be two distinct, sub-parallel WRC chemistry trends related to the two major petrographic textural facies identified: fragmental and coherent. It is recommended to conduct WRC Principal Component Analysis to fingerprint fragmental and coherent rock type magmas as this could have important implications for constraining diamond population sources. Preliminary studies of diamonds recovered from Tuzo in 2008 show highly comparable size frequency distributions for the various fragmental rock types of the geology model, which may be in part be explained by the multi-event volcanological mixing and mingling processes that are considered to have occurred during emplacement.

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Deep-sea Limu o Pele: The Significance of Bubble-wall Shards in Hyaloclastite Deposits

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Many cases have recently been documented where limu shards occur in sheet hyaloclastite deposits in the deep sea (800-3200 m below sea level (bsl)). Their model of formation accounts explicitly for mildly explosive interaction of seawater and lava under high confining pressure.

Deep-sea sheet hyaloclastite consists mostly of sand-sized blocky and splinter-shaped shards. They may also contain up to 25 % of mm-cm sized thin, curved, and wrinkled plates and sheets of sideromelane. This type of shards, termed Limu o Pele, has been observed forming subaerially in Kilauea by entrapment of water in flowing lava followed by expansion of steam to form large bubbles that burst into thin fragments. Deep-marine limu has been inferred, from comparative morphological studies and assessment of physical bubble-forming conditions, to form in a similar way. The increased ambient pressure and higher viscosity of water, however, reduces bubble expansion, and differing mechanisms of heat transfer and rates of magma chilling further modify limu-forming process in the deep sea.

The quantitatively supported model developed is based on observed limu forming processes and criteria derived from dive samples and observations at Seamount Six, Cocos Plate. It is inferred that water and/or water-saturated sediment was trapped in extremely thin, fluid and rapidly advancing lava flows by various processes. This is supported by an absence of limu-bearing hyaloclastite in sediment-free areas of e.g. the East Pacific Rise. Other bubble forming mechanisms, however likely, are not confirmed by collected samples.

Subaqueous limu formation appears to be restricted to basaltic compositions, as shards analyzed range from MORB to Hawaiiite, and to water depths greater than 800 m bsl. No shards have been described from shallow subaqueous deposits formed by highly explosive magmatic and hydrovolcanic magma-water interactions, nor from sediment-free areas. Limu-bearing hyaloclastite is thus interpreted to represent a good paleoenvironment and –depth indicator.

* Maicher, D. (2002) Deep-sea Limu o Pele: The Significance of Bubble-wall Shards in Hyaloclastite Deposits. AGU Chapman Conference on Explosive Subaqueous Volcanism, Dunedin, New Zealand, pp. 19-20.

Surtseyan volcanism over time and space exposed at Lookout Bluff, North Otago, New Zealand

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Cliffs at Lookout Bluff expose basaltic surtseyan successions, interbedded with fossiliferous Eocene marine siltstones. The volcanoclastics, mainly coarse-grained, comprise tuff breccias, lapillistones and tuffs. They are formed by shallow marine phreatomagmatic fragmentation of vesiculating magma. Sedimentary characteristics suggest deposition by primary submarine fallout, modified by contemporaneous re-sedimentation. Similar-style volcanoclastic deposits are found along the North Otago coastline from Oamaru in the north to Moeraki Peninsula in the south, including the locations Kakanui and Bridge Point.

Although original cone morphologies are not fully preserved and vent locations are ill-defined, flow direction and bedding orientations enable reconstruction of the architecture of the complex. Several monogenetic cones, with a slope angle of 20° - 35°, are closely spaced over an area of 4 x 1.5 km extent. The larger of these coarse-grained edifices possibly reached a maximum height of 80 m, still remaining submerged. Finer-grained deposits with a bedding dip of ca. 5° occur locally between cones. Morphological features used to constrain the sequence of events include (1) a sequence of sediment gravity flows, originating from 2 separate vents, interbedded and deforming one another, (2) discordant contacts between deposits of younger and older edifices, (3) large-scale flank failure with shearing along the basal siltstones and (4) syn-depositional slumps and faults.

Time factors represented in the Lookout Bluff area are complex and differ widely. The time required to produce a single volcanic edifice, each of which accumulated within hours to days, contrasts strongly with the length of volcanically quiet periods (indicated by conformably interbedded non-glaucconitic and glaucconitic siltstones). Furthermore, the timing of volcanic activity ranges from contemporaneous eruptions from two vents to activity widely spaced in time, which depicts the sporadic nature of the volcanism. Recurrence of volcanism similar in style and in close vicinity requires steady conditions and a local, long-lived magma supply.

* Maicher, D. (2002) Surtseyan volcanism over time and space exposed at Lookout Bluff, North Otago, New Zealand. AGU Chapman Conference on Explosive Subaqueous Volcanism, Dunedin, New Zealand, p. 37.

Architecture and development of a shallow marine tuff cone at Lookout Bluff, New Zealand

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Cliffs at Lookout Bluff, North Otago, New Zealand expose a complex of several monogenetic basaltic tuff cones within a succession of Eocene marine siltstones. The northern cone this case study focuses upon, possibly rose to a height of 80 m, still remaining submerged. The tephra consist of glassy, low-moderately vesicular sideromelane, indicating shallow marine phreatomagmatic fragmentation of vesiculating magma. Important sedimentary characteristics are planar bed geometries on outcrop scale, normal and density grading and incipient flow indicators, e.g. trains of larger clasts, absence of bomb-sags and subtle cross bedding. These suggest deposition by submarine fallout and eruption-fed density currents, some modified by contemporaneous resedimentation events.

Architecturally the early cone-forming facies is a tuff breccia in which initially flat-lying beds are covered by beds with increasingly steeper dips. Successive facies of tuffs and lapilli tuffs built the flanks. Important internal features are syn-depositional slumps and shear-faults, modifying the original cone shape syn- to early post-depositionally. The variability within and between lithofacies is explained by fluctuations in the subaqueous eruption style and vigour of explosions expelling tephra jets.

* Maicher, D. (2000) Architecture and development of a shallow marine tuff cone at Lookout Bluff, New Zealand. International Maar Conference, Daun/Vulkaneifel, Germany, 2000/6, Terra Nostra, pp. 309-317.

Bubble-wall fragments in deep-sea hyaloclastites: the formation of limu o'pelee

Doris Maicher and James D.L. White*

Deep-sea hyaloclastites commonly consist of non-vesicular, angular sand-to-granule sized sideromelane clasts. The blocky and splinter-like shards with extremely elongated, triangular cross sections are indicative of rapid quenching and thermal shock granulation of magma. A third shard type however is thought to demonstrate the occurrence of steam and "mild" steam explosivity: Hyaloclastites sampled at a depth of 1600-2000 m below sealevel on Seamount Six, East Pacific, contain fragile, glassy plates. The shards, up to 2 cm across, are characterized by gently curved and tabular forms. Some are folded and tack-welded where back-folded parts touch one another. Morphologically they resemble shards termed Limu O'Pelee, which are observed forming subaerially in Kilauea. Limu are fragments of burst magma bubbles formed by vaporization of water or water-saturated sediment entrapped by lava.

Rheological parameters, steam formation and heat transfer mechanisms are quantitatively assessed to constrain the growth processes of deep-marine magma bubbles. Steam expansion, which is increasingly suppressed with increasing water depth, controls the bubble size. Steam also forms a thin film around growing bubbles. Heat fluxes across a steam film, at high magma temperatures (1150°C), are similar to those of subaerial radiation, and this protects the hot magma from rapid chilling by direct magma-water contact.

Cooling of lava at the magma-steam interface, accompanied by an increase in viscosity and tensile strength, leads to the development of a surface skin, the future magma bubble-wall. Bubble growth on the surface of a lava flow is controlled by lava crust formation and time required for expanding a bubble versus cooling of lava during that process. Calculations show that the time-frame provided by cooling through a steam film is sufficient to allow deep-marine limu bubble formation.

* Maicher, D. & White, J.D.L. (2000) Bubble-wall fragments in deep-sea hyaloclastites: the formation of Limu O'Pelee. Volcanic and Magmatic Studies Group Annual Meeting, Sedbergh, U.K.

Sporadic shallow marine volcanic activity and associated sedimentation at Lookout Bluff, North Otago

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The Lookout Bluff volcanics in North Otago comprise a complex sequence of submarine basaltic volcanoclastics conformably interbedded with marine siltstones. The siltstones are glauconitic and fossiliferous (Kaiatan, upper Eocene), and were deposited in a tectonically stable, transgressive shelf setting. The volcanics belong to the Eocene-Oligocene Waiareka-Deborah volcanics of the North Otago volcanic province. At Lookout Bluff, cliff exposures of vesicular pyroclastic breccias, lapillistones and tuffs show massive to well-bedded sequences with normal grading and density grading, faint alignment of clasts and minor ripple and dewatering structures. The glassy, poorly sorted clasts are mostly angular with fracture-bound surfaces transecting vesicles. Facies associations and clast characteristics imply phreatomagmatic fragmentation at shallow depth and subaqueous deposition. Sedimentary characteristics suggest deposition by primary pyroclastic falls, modified by penecontemporaneous resedimentation processes.

The volumetrically small deposits, with a wide variety of bedding dips, are interpreted as several small, monogenetic cones, each of which accumulated within hours to days of activity. They are closely spaced over an area of c. 4 x 1.5 km extent, including offshore platforms with lineations of volcanic erosional remnants. Vent locations are ill-defined, but flow direction indicators and dips of beds enable the architecture of the cone field to be reconstructed.

Time between each cone is recorded by (a) direct interfingering of volcanoclastics from different cones, (b) non-glauconitic siltstone interbedded conformably within a tuff sequence, and (c) glauconitic siltstone deposited conformably between overlapping volcanoclastic deposits, derived from different source directions. In (a), penecontemporaneous eruption from two separate, closely spaced cones resulted in intimate interfingering of gravity flows with reciprocal overriding and deformation. In cases (b) and (c) a time break is indicated by bioturbation in the uppermost volcanoclastic horizon and siltstone deposition, indicating re-colonization by benthic fauna during a period of volcanic quiescence. The actual time elapsed between volcanic activity is estimated by calculating sedimentation rates of siltstone (c. 20 m/Ma on North Otago shelf), the time required to form glauconite (10^3 - 10^6 yrs, depending on maturity of glauconite) and by microfossil dating. Thus, moments of volcanic activity contrast strongly with extended periods of silt deposition during volcanic quiescence.

* Maicher, D. (1998c) Sporadic shallow marine volcanic activity and associated sedimentation at Lookout Bluff, North Otago. Geological Society of New Zealand & New Zealand Geophysical Society joint annual conference, Christchurch, New Zealand, Geological Society of New Zealand Miscellaneous Publication 101A, p. 154.

DEEP-SEA "LIMU O'PELEE" FORMATION

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A detailed submersible study concentrated on deep-sea sheet-hyaloclastite and associated lava flows on Seamount Six, Cocos Plate. Blocky, angular shards of sand to granule-size, mixed with up to 40% of sliver-shaped *limu* (formed by bursting thin-walled magma-bubbles, expanded by trapped water), form sheet-like deposits, which show evidence of deposition from turbulent lateral gravity flows. Shards, *limu* and lava in individual samples reveal a range of basaltic compositions, ranging from MORB to Hawaiiite, suggesting several sources of magma, erupted ~ contemporaneously and mixed in single hyaloclastite beds.

Common occurrence of *limu* shards under submarine high confining pressures in the study area suggests favourable conditions, as such shards are rare subaerially. The formation of lava bubbles, controlled by, e.g., steam expansion, rheological properties of magma and protecting steam carapace, is apparently independent of magma geochemistry.

A hot, fluidal magma, which moves rapidly, is required to mingle with seawater. Possible settings are (1) lava flowing over water-saturated sediment, (2) a small lava fountain or (3) collapsing pillow tubes. Supporting evidence for the first option are contorted lava mounds and pelagic ooze incorporated in hyaloclastite, secondly spatter-like deposits and thirdly, hollow drained pillows.

Understanding *limu* formation will help to constrain interpretation of sheet hyaloclastite eruptive style, as well as fundamental controls on steam explosivity under high confining pressures.

* Maicher, D. (1998a) Deep-sea "Limu O'Pelee" formation. International Volcanological Congress, Cape Town, South Africa, IAVCEI, p. 38.

Formation of deep-sea hyaloclastite on Seamount Six, Pacific Ocean

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A detailed submersible study with DSV Alvin focuses on eruptive and depositional processes of basaltic sheet-hyaloclastite on Seamount Six, a ca. 2 ma old volcano off-axis the East Pacific Rise. Hyaloclastite occurs highly localized on the summit plateau and on benches of the upper flanks at a depth of 2000-1675 m below sea level. Individual deposits have an areal extend of several m² and are found in close association with pelagic sediment and very thin sheet flow lava, which is often disrupted and contorted.

The deposits consist of non-vesicular, blocky and splinter-shaped shards in sand-to-granule size, admixed with copious amounts of sliver-shaped *limu* (formed by bursting thin-walled magma-bubbles, expanded by trapped water). Multiple successions consist of 3-5 cm thick beds with sedimentary structures and entrained lithics and pelagic ooze, indicative of deposition from turbulent gravity flows. Geochemical analysis of shards and associated lava flows reveal a range of basaltic composition in individual samples, ranging from MORB to hawaiiite, erupted ~ contemporaneously.

Similarity in composition and field evidence of disrupted lava spalling off fragments suggest that shards are derived from fragmented lava flows of either type, and mixing occurred during turbulent gravity flow.

One hypothesis is the rapid exsolution of magmatic volatiles driving a small lava fountain. This model is supported by spatter-like deposits, but neglects the scarcity of vesicles and the absence of apparent feeder vents.

More likely is that hyaloclastite form from lava covering sediment ponds and heating the enclosed pore water. Rapid expansion of pressurized steam disrupts the lava and induces rapid and extensive thermal shock granulation, as well as limu bubble formation. The latter is controlled by e.g. steam expansion, rheological properties of magma and protecting steam carapace. Understanding limu formation will help to constrain the interpretation of sheet-hyaloclastite eruptive style, as well as fundamental controls of steam explosivity under high confining pressures.

* Maicher, D. (1998b) Formation of deep-sea hyaloclastite on Seamount Six, Pacific Ocean. Advanced study course 1998: Volcanic hazard assessment, monitoring and risk mitigation, Furnas, Sao Miguel Island, Azores, p. 81.

Detailed sedimentary study of deep-sea hyaloclastite, Seamount Six, Pacific

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In 1995, submersible Alvin was used to study basaltic deep-sea hyaloclastite on Seamount Six, Cocos Plate, at 1600-2000m depth. Hyaloclastite occurrences on the flattish summit and benches along the upper flanks are in close association with pillow lavas, sheet flows and pelagic sediment.

Hyaloclastite sheets consist of multiple successions of 3-5 cm thick sedimentary units. Non-vesicular sand-to-granule sized shards are blocky and splinter-shaped, with varying amounts of flaky and wrinkled limu (= large, thin-walled lava bubbles, expanded by trapped water). Different shard types seem to be sorted according to their individual settling velocities. Sedimentary structures, such as massive to normal grading, scour around blocks, imbrication and cross bedding, as well as entrained lithics and microorganisms, indicate turbulent flow.

To constrain type of flow and flow behaviour, more information on changes of hyaloclastite texture over distance is needed. Detailed surveying of a 100 x 100 m area with closely spaced dive transects yielded several hours of video coverage and 10 large rock samples.

Available evidence suggests deposition from a small-volume gravity flow, that gained momentum by the gravitational head of some eruptive column. It might be modified by observed strong ocean currents on the seamount.

* Maicher, D. (1997) Detailed sedimentary study of deep-sea hyaloclastite, Seamount Six, eastern Pacific Ocean. Geological Society of New Zealand annual conference, Wellington, New Zealand, Geological Society of New Zealand Miscellaneous Publication 95A, p. 111.

New evidence from Alvin for the origin of deep-sea eruptive hyaloclastite on Seamount 6: Cocos Plate, 12°43'N

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In Oct.-Nov. 1995 we used DSV Alvin, the MBARI rock drill and a WHOI bottom 35 mm camera to study eruptive deep-sea (1800-2000 m) hyaloclastite deposits on Seamount 6, on the Cocos Plate (ca. 3.0 Ma crust). During 9 dives we collected 69 samples of hyaloclastite and associated lava flows and 12 short (<10 cm) drill cores of mostly thin-bedded hyaloclastite units. The dives and 9 camera tows were concentrated in a small (ca. 1.5 km x 1.5 km) area of the upper south flank of Smt. 6 including two smaller (100 m x 100 m) detailed study areas.

Abundantly exposed hyaloclastite surfaces are mantled by thick (1-2 cm) Mn and partly covered by pelagic sand. Individual eruptive units commonly consist of thin (3-6 cm), highly contorted glassy flow units overlain by apparently coeval fragmental material. The flow units are commonly flow-banded, have large (up to 10 cm) closed ovoid and cylindrical vugs partly filled with pelagic ooze, and contorted flame structures apparently shedding glass fragments into the overlying and adjacent hyaloclastite. The hyaloclastite is bedded, has normal grading and typically is poorly sorted, including lithics up to several cm. Glass shards in the hyaloclastite comprise at least two populations: 1) chemically identical to the flows (hawaiite or primitive MORB), and 2) extremely primitive MORB with up to 10 wt.% MgO. Available evidence suggests these units form from rapidly-erupted, low-viscosity flows that mix with seawater and/or pelagic sediment, producing shards by several mechanisms.

* Batiza, R., Becker, N., Bercovici, D., Coleman, T., Gorman, T., Head III, J.W., Holloway, L., Karsten, J., Kelly, A., Keszthelyi, L.P., Maicher, D., Mueller, W., Muller, J., Norby, L., Paduan, J., Parker, G., Prockter, L., Stakes, D. & White, J.D.L. (1996) New Evidence from Alvin for the origin of deep-sea eruptive hyaloclastite on Seamount 6: Cocos plate, 12°43'N. American Geophysical Union meeting, San Francisco, USA, Eos, Transactions of American Geophysical Union Supplement 77, p. 319.

Multiple, mixed hyaloclastite flows on Seamount Six, Pacific Ocean

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In 1995, DSV Alvin, a deep-tow camera and a portable rock-drill were used to study basaltic deep-sea hyaloclastite on Seamount Six, a c. 2 Ma old volcano off-axis along the East Pacific Rise on the Cocos Plate. The multi-national project aims to determine eruptive style, fragmentation and depositional processes of well-bedded, thin sheets of volcanic fragmental glass at 1800-2000 m depth bsl.

During 9 dives, we encountered extensive blankets of hyaloclastite on the more gently sloping flanks of the seamount. Commonly associated are tube-fed pillows, lava talus and thin, contorted sheet lava. Thick (1-2 cm) knobby Mn-crust mantles all rock surfaces and abundant pelagic ooze camouflages the outcrops.

The 69 recovered hyaloclastite and lava samples and 12 short drill cores often have multiple beds of hyaloclastite. Individual beds are usually normally graded, poorly sorted and show flow structures around such obstacles as lava talus blocks. Lithic clasts and pelagic microorganisms are incorporated in the semi-consolidated hyaloclastite. All of these sedimentological characteristics indicate deposition from turbulent flows. Successions of flows are either concordant or paraconform, separated by pelagic sediment and/or Mn-layers, indicating time breaks between deposition of single flows. Underlying sheet lava is flow-banded and folded with little vugs. Its glassy crust is broken in pieces and apparently contributes to the hyaloclastite.

The entirely non-vesicular glass shards are mostly blocky, with minor proportions of platy and limu shards (=flakes of large, thin-walled bubbles, expanded as entrapped water forms steam). The limu shards are often concentrated in distinct horizons. Shard shapes and their context suggest several fragmentation processes, including quench-granulation, spalling from lava flows, and steam expansion. The absence of vesicles exclude comminution by magmatic explosivity.

Geochemically, the shards group in at least 3 populations: 1) Hawaiiite, 2) depleted MORB and 3) very primitive MORB. Compositions 1) and 2) also occur as lava flows associated with chemically identical shards. Optically, hyaloclastite and lava glass vary in colour from very light to dark brown, and shows different refractive indices, perhaps as a result of differences in the rate of cooling and/or in composition. However, neither the observed color variation of the shards nor the flow-banding of the lava have yet been demonstrated to coincide with compositional variation.

Preliminary result suggest shard production from rapidly-erupting magma by a variety of fragmentation processes. Mixing of shard types and incorporation of pelagic material took place during emplacement as turbulent flows.

* Maicher, D., White, J.D.L. & Batiza, R. (1996) Multiple, mixed hyaloclastite flows on Seamount Six, Pacific Ocean. Geological Society of New Zealand annual conference, Dunedin, New Zealand, Geological Society of New Zealand Miscellaneous Publication 91A, p. 116.

A Multiple Vent Sequence of a Shallowing-Up Marine Volcaniclastic Complex at Lookout Bluff, New Zealand

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Cliff exposures at Lookout Bluff, North Otago, display a shallow marine sequence of Eocene - Oligocene basaltic volcaniclastics. Well bedded, vesicular pyroclastic breccias, lapillistones and tuffs are interbedded with continental shelf siltstones. Discontinuous volcanic activity with shifting vent positions produced primary fall and flow deposits, which have been partly modified by resedimentation processes. Facies associations and clast characteristics imply phreatomagmatic fragmentation and subaqueous deposition. Eruptions from ill-defined vents were sporadic and of small volume. Deposits are characterised by breccia-like massive pyroclastics and/or bedded tuffs of slightly vesiculated sideromelane.

Rising magma caused uplift and distortion of the deposits, resulting in complex relationships between overlapping volcaniclastics. In the later stages, increasing volcanic activity became focused in a central vent producing massive to faintly layered, highly vesicular, tachylitic lapillistones and tuff breccias. Progressive shallowing due to continued volcaniclastic deposition, together with the higher eruption rate, limited water access into the vent. Consequently, magmatic fragmentation then became dominant over hydroclastic fragmentation.

* Maicher, D. (1996) A multiple vent sequence of a shallowing-up marine volcaniclastic complex at Lookout Bluff, New Zealand. Western Pacific Geophysics Meeting, Brisbane, Australia, Eos, Transactions of American Geophysical Union Supplement 77, p. 126.