been formed by very deep and hot melting. Others have suggested that they are olivine cumulates, supported by the large, abundant olivine grains in the lavas, because the linear compositional trends in major elements of all the meimechite bulk compositions are consistent with an accumulation or loss of olivine. The high concentration of incompatible elements of the lavas also may suggest either a lithospheric component, a very small degree of mantle melting, or possibly magma mixing. The very high liquidus temperature for this composition is a strong contraint on processes of formation for the Siberian flood basalts, and as experiments are performed at higher temperatures, suggestions for the mantle source lithology will be discovered.

V32A-1005 1330h POSTER

Link Between Volcanism and Mantle Exhumation at the Axial Zone of a Fossil Slow Spreading Ocean

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Within an axial zone of a slow spreading ocean, the mechanisms checking together volcano emplacement, mantle exhumation and ocean enlargement are poorly known. In order to better assess how they are linked, a detailed study of a fossil ocean-floor structure, preserved from alpine tectonic and metamorphism, was performed in the Chenaillet unit (Franco-Italian Alps)(Chalot-Prat et al, submit.). The 3D geometry of the ophiolite evidences that from its dimensions, topography, morphology and the architecture of the basaltic cover, the Chenaillet unit is a witness of an axial zone of Atlantic type. The basement (serpentinized peridotites; gabbros), below and on both sides of the volcanic cover, is capped by cataclasite horizons underlining detachment faults responsible for its exhumation at the seafloor. Clasts of basalt found within the cataclasite indicate an active exhumation during and after volcano emplacement. Stair- and Comb-type volcanic systems check the distribution of individual volcanoes. The higher the edifice, the younger it is relative to the others. In a S-type, each step is formed with a pillow and tube tongue stacking fed from fissures located at the root of each step. The system formed by uplift, step by step fracturation of an already exhumed basement, and magma injection along the fissures. A C-type consists in alignments of pillow and tube conic edifices. Their central feeder dykes are located at the crossing of fractures oblique and parallel (line) to the main branch of the comb. Along a same line, eruptions are coeval. The comb formation needed initial basement fracturation, then uplift and exhumation of a new basement along a detachment fault which also controlled magma injection. Once formed, volcanoes were dragged away and down on the travelator to give place to new volcanoes. The pseudo-symmetry of the C-type evidences that the exhumation process occurred synchronously, but not at the same rate, in opposite directions, as observed at any mid-oceanic ridge axis. In both systems, fast alternation between partial melts and their differentiates suggest that the main magma conduits were rooted within frequently fed small reservoirs. The regular recurrence of partial basaltic melts also suggests that the main conduits were rooted within the mantle source. Lithospheric stretching could control both magma ascent and mantle melting.

V32A-1006 1330h POSTER

Origin Of Extreme $^3He/^4He$ Signatures In Icelandic Lavas: Insights From Melt Inclusion Studies

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Helium isotopes are considered a powerful tool for tracking different mantle domains. Yet, the origin of He isotope variations in many basaltic suites remains enigmatic and often difficult to link with more lithophile chemical and isotopic tracers. One problem is that He isotope ratios are measured from crushed olivines and thus reflect prior fluid and melt fluxes trapped in inclusions within the olivine grains, whereas the lithophile elements mainly reflect the host lava. In an attempt to link He and lithophile element variations, we have characterized the major and trace element composition including volatile elements, of olivine-hosted melt inclusions from three ankaramitic lavas from Vestfirdir, NW-Iceland. Previous studies have reported extreme $^3He/^4He$ ratios from NW-Iceland and one ankaramite (SEL97) has been suggested to provide the most precise estimate of the radiogenic (Sr-Nd-Pb) isotopic composition of a relatively undegassed (high $^3He/^4He$) mantle component (C or FOZO) common to several ocean islands (Hilton et al. 1999, EPSL 173, 53-60). The samples investigated here exhibit amongst the highest $^3He/^4He$ ratios observed in terrestrial rocks (42.9 and 34.8 R/R_a). A detailed account of the trace element signature of melt inclusions in these samples may thus help explain the origin of FOZO. One sample of similar composition to these, has a lower He content and a relatively poorly defined He isotope composition of 8.15 ± 5.1 R/R_a (Breddam & Kurz, 2001, EOS, 82, F1315). In terms of major elements, the whole rock data reflect olivine accumulation, whereas the melt inclusion data reflect ol + cpx fractionation. The melt inclusions are generally basaltic (Mg#: 52-62), with primitive mantle normalised trace element concentrations that are broadly parallel the host lavas. There is little compositional difference between melt inclusion populations from high and low $^3He/^4He$ lavas, although inclusions of the low $^3He/^4He$ lava have lower S and moderately lower Cl. The observed range of trace element ratios: $[La/Sm]_N$ 1-4, $[La/Yb]_N$ 1-5, Sr/Nd 14-24, Ba/Rb 9-23, and Ce/Pb 5-46, covers much of the range observed in Icelandic alkali basalts. The compositional similarities between inclusions and host lavas suggests that bulk rock compositions are petrogenetically related to the melts sampled by melt inclusions. If He predominantly resides in these inclusions, it suggests that the whole rock composition is an aggregate derived from the same melts that contain the measured He.

V32A-1007 1330h POSTER

He-Ne systematics in OIB and the nature of the source of mantle plumes

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We have designed a new extraction and purification line, fully automated, coupled with our glass mass spectrometer ARESIBO I, equipped with a faraday cup and an ion counting system. The very low CO2 and 40Ar levels of the machine allow us to analyze the neon isotopic composition in very small samples. We have performed helium and neon analyses on olivine phenocrysts from different oceanic island basalts (St Helena, Gough, Tristan, Azores, Kerguelen, Hawaii). Most of the samples present anomalies compared to air for neon (with ratio 20Ne/22Ne up to 11.67) and all the data plot between the MORB line (e.g. Sarda et al. 1988) and the Iceland line (e.g. Moreira et al., 2001). Corrected for air 21Ne/22Ne ratios (assuming a solar 20Ne/22Ne) are between 0.036 and 0.081. In a diagram 21Ne/22Nec versus 4He/3He, all the OIB plot between a mean MORB composition and a solar like composition, and can be interpreted as a binary mixing with a r=(3He/22Ne)MORB/(3He/22Ne)solar parameter for the hyperbolae around 10 suggesting that mixing between the plume material and the MORB material occur in liquid condition. Another interpretation is that the 3He/22Ne of the MORB source is higher from the solar 3He/22Ne which appears in contradiction with previous estimates. Nevertheless, our conclusion is that the neon is a better tracer of primordial material than helium.

V32A-1008 1330h POSTER

State of mantle (re-)mixing and large igneous provinces

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Large igneous provinces are the largest expression of magmatism on the Earth, and they are usually associated with hypothetical mantle plumes, thereby playing a fundamental role in forming a currently prevailing view of mantle dynamics; mantle convection is characterized by large-scale plate-tectonic circulation and small-scale plume upwelling. The actual origins of large igneous provinces are, however, still poorly understood. In this contribution, I review geophysical and geochemical constraints on the origin of the North Atlantic igneous province, which is one of the best-studied provinces. By combining various constraints ranging from mantle and crustal tomography to igneous petrology and geochemistry, I suggest that this igneous province has most likely resulted from strong chemical heterogeneity in source mantle without notable thermal anomaly. A long-standing dynamical problem regarding the upwelling of fertile (thus dense) mantle is also shown to be resolved by considering the physics of a self-contained whole-mantle convection system. The significance of chemical heterogeneity in the genesis of large igneous provinces may not be limited to the North Atlantic province. The efficiency of convective remixing is not expected to be globally uniform, which implies that spatially variable mantle composition is a natural outcome. The distribution of large igneous provinces may simply reflect the pattern and intensity of such inherent chemical heterogeneity in convecting mantle.

V32B MCC: Level 2 Wednesday 1330h

The First Historical Eruption of Anatahan Volcano, Mariana Islands Posters *(joint with T)*

Presiding: **D Wiens,** Washington University**; T Fischer,** University of New Mexico**; D Hilton,** Scripps Institution of Oceanography**; J T Camacho,** Emergency Management Office, Capitol Hill

V32B-1009 1330h POSTER

The First Historical Eruption of Anatahan Volcano, Mariana Islands

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The first historical eruption of Anatahan volcano occurred on May 10, 2003. The MARGINS office responded by authorizing helicopter surveillance and ship deployment to visit the volcano. The helicopter flight on May 19 allowed visual observations and identification of the east crater as the source of the eruption. The top of the plume was estimated to be at 10,000 ft - significantly less than the 30,000 ft of the initial blast. No bombs were ejected out of the east crater at this time but were falling back into the crater. The bombs looked irregular in shape, massive and were estimated to be a few m in diameter. Bombs and tephra samples were collected from the eastern side of the island when blasts were occurring at a rate of approx. 1 per 5min. The ship visit followed on May 21 to the western side of the island for collection of samples and SO_2 flux measurements, along with maintenance of a previously deployed seismometer.

Volcanic samples collected on Anatahan consisted of bombs, ash and scoria from the present eruption and old lavas (age unknown). The ash section on the western shore was 25 cm thick and consisted of the following sequence (bottom to top): 0-5 cm: grey/tan layer fine ash coarsening upward to sand size, 5-8 cm: well sorted accretionary lapilli (2-3 mm), 8-20cm: inversely? graded dark ash with scoria and pumice clasts (1-2 cm), 20-25 cm: well sorted clast-supported scoria (max 2 cm) with some fine ash. The maximum total thickness measured at a site 6 km from the east crater was approximately 45 cm. The sequence is interpreted as 1) initial blast 2) interaction of magma with water (from pre-existing hydrothermal system) as evidenced by accretionary lapilli 3) magmatic phase of the eruption producing juvenile material. Electron microprobe analyses of the pumice and scoria show uniform compositions of 60wt% SiO_2 in the glass; zoned plagioclase with average composition of 61% An, 37.7% Ab, 1.2% Or; pyroxenes (19.4% Wo, 53.4% En, 26.7% Fs) and Fe-Ti oxides. Sulfur and Cl contents are approx. 100 and 1500 ppm, respectively. Water content of the glass may be several wt% based on analytical totals.

Volatile emissions from the volcano were measured by traversing under the plume with a ship-based COSPEC.

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Using wind speed data from NOAA (10-15 knots on May 21), we estimate the daily SO_2 flux to be 3000 - 4500 tons. Our observations are consistent with the idea that the initial phreatic eruption evolved rapidly into a magmatic phase producing juvenile (and vesicular) material accompanied by a high SO_2 flux. Details on the eruption products, chemical analyses, seismic measurements, and current monitoring efforts can be found in accompanying posters.

V32B-1010 1330h INVITED POSTER

The Anatahan Felsic Province in the Mariana Arc System

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The May 2003 plinian eruption of Anatahan was a surprise for the residents of the Northern Mariana Mariana Comonwealth (USA). From a petrologic perspective, this eruption of siliceous andesite was also atypical for the Mariana arc, which elsewhere mostly erupts fractionated basalts and basaltic andesites. However, felsic eruptions are not unusual for Anatahan which has previously erupted a wide range of lavas, from basalts through dacites. The reasons and significance of the intermittently felsic nature of Anatahan lavas may reflect either development of a mature magma chamber localized beneath Anatahan or perhaps the presence of an areally-extensive pool of felsic magma in the middle crust, similar to that inferred for the Izu arc to the north. Anatahan lies at the southern end of the Mariana Central Island Province and just north of the Southern Seamount Province, but it has never been clear whether these morphological subdivisions reflect different magma fluxes along the arc or are due to the island volcanoes being older than the seamounts. Synthesis of existing data for Anatahan and data for surrounding seamounts collected during the 2001 Cook 7 expedition and earlier cruises indicates that Anatahan is situated near the middle of an arc segment with an unusually high proportion of felsic lavas compared to typical Mariana Arc magmatic products. The 115 km-long arc segment from E. Diamante seamount East Diamante seamount (15°55'N) to a seamount NW of Zealandia Bank (17°N) define the Anatahan Felsic Province (AFP). Seven edifices within this region, including Anatahan, have erupted felsic lavas, often interspersed with more mafic lavas. Volcano size does not seem important in controlling the abundance of felsic lavas within the AFP; the volcanic island of Sarigan does not contain felsic lavas, whereas small parasitic cones NE of Anatahan and SW of E. Diamante erupt lavas with 65% and 72% SiO2, respectively. This region also contains two suspected hydrothermal vents, as identified by a 2003 NOAA cruise (see Embley et al. T05 IBM arc session). AFP lavas define a consistently medium-K, calc-alkaline suite. There are no large, well-defined calderas as have been mapped in the Izu arc segment to the north. The clearest calderas in the AFP are those of Anatahan and E. Diamante volcanoes, both of which have similar, E-W elongated, craters. The abundance of felsic lavas associated with complex bathymetry west of Sarigan and Zealandia Bank may manifest a large caldera complex that has been overprinted by post-collapse volcanism; more field work will be needed to test this hypothesis. The abundance of felsic lavas in the AFP is difficult to explain by the development of magmatic reservoirs that allow fractionation beneath individual volcanoes. The regional nature of felsic magmas in the AFP supports explanations that call for these to be developed in a broad zone within the middle crust of the region, similar to that envisioned for the Izu arc segment. It would be useful to know if the unusually high abundance of felsic lavas in this region is associated with a mid-crustal layer with seismic velocities characteristic of tonalitic plutonic rocks, as has been found for the Izu arc to the north.

V32B-1011 1330h POSTER

Geological Characteristics of the 2003 Eruption at Anatahan, Northern Mariana Islands

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During GPS campaign of the Northern Marianas, we carried out geological inspection about the May-June eruptions at Anatahan, landing on 8 points within the island in mid-July. The active crater, located at the bottom of the eastern caldera, has the dimension of about 300 m across and 100 m deep, and wreck of a lava dome, whose appearance was witnessed first in early June, was observed in the northern periphery. The highest temperature measured within the crater was as high as about 300 C, the crater bottom was filled with mud poured into from the surrounding steep walls. Tephra of the eruptions is thicker in the western part: up to about 1 m thick in the western caldera. Small rills and gullies grow extensively over the deposits. Total volume of eruption products can be roughly estimated at a few tens of million m3. Deposits are composed basically of lower brown and upper gray tephra layers. Both consisting of pyroclastic fall and surge deposits. Brown tephra layer contains various colored vesicular pumice, and larger and denser pumice is accumulated in the uppermost part. Gray tephra is very fine ashes, even on crater rim, deposited by falling including a lateral movement from the crater side. Though some of them were burnt in surge deposits near the crater, vegetation had stood during deposition of brown tephra and was toppled down by deposition of gray tephra. A block probably of broken lava dome is covered only by gray tephra. All pumices, block of lava dome, and masses of brown and gray tephra are andesitic in composition (60-61 % SiO2). Following the eruptive activity of brown tephra since mid-May, another explosive event of phreatomagmatic eruptions occurred probably in mid June, the latter was just preceded by breaking of newly-formed lava dome. As the active crater probably was deepened with time during eruptions, magma reacted with water invaded from aquifer or sea, resulting in the explosive eruptions. Only finer particles of quenched and fragmented magma spilled over rims of deepened crater.

V32B-1012 1330h POSTER

Geochemical Composition of Volcanic Rocks from the May 2003 Eruption of Anatahan Volcano, Mariana Islands

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The first historical eruption of Anatahan volcano began on May 10, 2003, from the easternmost of the island's two craters. Samples of tephra, scoria, and bombs, collected in May by a MARGINS-supported rapid-response team, were analyzed for 34 trace elements by solution ICP-MS at Boston University and Sr-Nd-Pb isotopic composition at the University of Texas-Dallas. The new eruptive materials can be compared with an extensive suite of pre-existing volcanics (basalts through dacites) from Anatahan sampled by the USGS in 1990 and 1992, and analyzed by XRF and INAA. While most Mariana volcanoes erupt basalts and basaltic andesites, Anatahan is unusual for erupting a wide range of compositions, from basalt to dacite, and thus provides the best opportunity for addressing questions of magma evolution in this classic island arc. The newly erupted scoria and pumice are andesites and dacites that are among the most silicic materials erupted in the northern Mariana islands. The recent eruptives are highly homogeneous; 13 samples vary by only 3-5% relative standard deviation for incompatible trace elements. Isotopic compositions (0.703450 +/- 2 87Sr/86Sr and 18.806 +/- 5 206Pb/204Pb) are within the range of previously measured samples from Anatahan and other volcanic centers in the Marianas. The combined dataset for Anatahan defines virtually a single liquid line of descent. This is consistent with nearly-parallel REE patterns, and small variations in the ratios of the most incompatible trace elements (e.g., Th/Rb varies by <10% over the entire fractionation trend). Low values of Th/La and Th/Zr in Anatahan volcanics provide evidence against partial melting of crustal material as a source of the silicic magmas, as these ratios are highly senstive to apatite- and zircon-saturated crustal melts. Instead, the basalts, andesites and dacites of Anatahan appear to be related predominantly by crystal fractionation with little evidence for assimilation of crustal melts. The new data can also be used to make new inferences as to the source characteristics of Anatahan magma. Trace element ratios Th/La and Sm/La distinguish island-to-island differences in the subducted sediment components incorporated into the Mariana arc magmas. Most Mariana volcanics plot on a mixing line between depleted mantle and the bulk subducting sediment Th/La (0.14). Anatahan, however, mixes to slightly higher Th/La (0.16), which could be caused by the shallow loss of the top 50 m of the sedimentary column (pelagic clay) during subduction.

V32B-1013 1330h POSTER

^{210}Pb and ^{210}Po Abundances in Dacites Erupted May, 2003 From Anatahan Volcano: Implications for the Time-scales of Magma Generation and Degassing

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Six samples of dacite pumice and scoria erupted in May, 2003 and collected from a number of sites around Anathan by Tobias Fischer and David Hilton were analyzed for ^{210}Po activities on three occasions between early June and the time of this writing. With two exceptions, all scoria and pumice samples have ^{210}Po activities that plot on a single growth curve indicating initial (^{210}Po)=0.15 $\pm$0.07 (1σ) dpm/g and (^{210}Pb)=1.08$\pm$0.20 dpm/g. More precise values for these initial activities will be presented at the meeting after further analyses are performed in November. Preliminary alpha spectrometry analyses for U and Th, and ICPMS analyses distributed by Terry Plank suggest that the average (^{238}U) is about 0.53 dpm/g. Equilibrium (^{228}Th)/(^{232}Th) ratios indicate that these samples do not have excess ^{228}Ra. Assuming that (^{210}Pb)< (^{226}Ra) because of minor degassing of ^{210}Pb (see Gauthier and Condomines, 1999, EPSL, v. 172), the degassing efficiency factor for ^{210}Po is greater than or equal to about 0.85, which is identical to the value calculated for a basaltic andesitic lava from Arenal volcano in Costa Rica (Gill et al., 1985, GRL, v. 12). This is surprising, as the May 10 plinian eruption of Anatahan should have resulted in more closed-system degassing than a lava eruption. This and the similar ^{210}Po values for the scoria and pumice samples suggest that the shallow-level degassing history has little impact on the efficiency of polonium degassing. The scoria and pumice samples from sample 8-1e both have significant excesses of ^{210}Po over the calculated initial (^{210}Pb) value for the other samples. These excesses were partially leachable, indicating that ^{210}Po was sublimated onto these samples, and that these ejecta resided in the vent before being ejected and redeposited The high inferred (^{226}Ra)/(^{230}Th) for the Anatahan dacites despite the nearly equilibrium (^{238}U)/(^{230}Th) value measured for one sample contrasts with the values for these ratios in more mafic Mariana samples, which are characterized by a direct correlation between radium and uranium excesses (Turner et al., 2001, Science, v. 292). Assuming that these trends hold up after additional analysis, the most straightforward interpretation of our alpha spectrometry data is that the dacite was generated by distillation of more mafic intrusives over a period of time that is significant compared to the half-life of ^{230}Th, and that radium was added to the dacite recently either by inmixing a Ra-enriched basalt or a crust-derived fluid.

V32B-1014 1330h POSTER

Oxygen isotope geochemistry of the May 10th Anahatan eruption.

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The Anahatan Eruption provides an opportunity to examine, in detail, the oxygen isotope chemistry of a zero age pyroclastic eruption. The petrology and trace element geochemistry of oceanic arc magmas is highly influenced by the introduction of subducted material to the mantle wedge. Oxygen isotope ratios, though sensitive to the addition of slab materials to the mantle, are also modified by fractional crystallization and contamination of magmas and sub-solidus alteration. In addition, trace element geochemical variations are found within single lava flows [1]. Zero age samples allow analysis of groundmass free of alteration minerals and the intensity of sampling provides coverage of geochemical variation within products of an individual flow. We report oxygen isotope ratios from 12 Anahatan samples that include lava, tephra, and a volcanic bomb. Our purpose is to compare Anahatan samples to each other and to other arc volcanoes and to assess oxygen isotope ratio heterogeneity within this single eruption. We determined oxygen isotope ratios for groundmass from all twelve samples. Lava sample δ^{18}O values vary from 5.5 to 6.1$^{o}/_{oo}$, with an average value of 5.9$\pm$.3$^{o}/_{oo}$. Tephra samples were separated into two vesicular, glassy fractions based on color and inclusions. The dark, oxide-bearing fraction has an average δ^{18}O value of 5.63 $\pm$ .07$^{o}/_{oo}$ (n = 8) while the light, oxide-free fraction has an average δ^{18}O value of 5.86 $\pm$ .08 $^{o}/_{oo}$ (n = 7). These fractions may not represent the bulk chemistry of tephra samples. Electron probe analyses are needed to characterize the major element chemistry of selected grains. The average oxygen isotope ratio of all Anahatan groundmass samples, 5.70$\pm$.3 $^{o}/_{oo}$, is typical for an oceanic arc and is similar to previously observed δ^{18}O values in Mariana arc volcanoes [2]. Lava oxygen isotope compositions are consistent with oxygen isotope fractionation by crystallization with high δ^{18}O values in silica-rich samples (>60 wt % SiO_2) and low δ^{18}O in a silica-poor sample ($\sim$ 50 wt %). The uniform oxygen isotope composition within each tephra groundmass fraction, over a range in silica content that is comparable to the range in lava silica content, is unexpected and is likely due to our selection of visually similar grains that do not reflect the heterogeneity of the bulk sample. The .26$^{o}/_{oo}$ fractionation between light and dark fractions of tephra groundmass may be a due to bulk composition, fractional crystallization, or variable degassing history. [1] Maclennan et al. (2003) JGRb 108, art. Number 2007 [2] Ito and Stern (1985/86) EPSL 76, 312-320

V32B-1015 1330h POSTER

GPS Observations in Anatahan Island, Northern Mariana Islands, Before and After the Eruption of May 10, 2003

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A GPS observation project in the Northern Mariana Islands started in 1992 by a joint team of Japan, US and Saipan, CNMI. We have repeated surveys in the area for several times until 2003. Previous results until 1999 showed clear evidence of back arc spreading at the Mariana Trough with velocities of 4-6cm/yr with respect to the Philippine Sea plate. There was no significant volcanic activity in this time periods. Anatahan Island erupted about three months after the latest resurvey of January 2003. In order to investigate crustal deformations of the island related to this eruption, we established a permanent site in Anatahan (ANAT). The site is located about 7km WNW of the active crater in the eastern caldera. Solar panel and a lead battery are used for power and a small PC is used for automatic data archive. A special stainless pillar was designed to set up right above the pre-occupied benchmark. We also established a new permanent site in Saipan on the roof of EMO (EMO1). For a tie to the old site in Saipan, we conducted a survey at MPLC site that have been repeatedly occupied. For a preliminary analysis, we used data sets of 1994, 1998, 1999 and January and July of 2003 for a baseline MPLC - ANAT. The obtained results suggest that Anatahan has linearly drifted to northwest relative to Saipan at least until January 2003 with a rate of about 6.5mm/yr. There was no clear long-term vertical motion of Anatahan Island until January 2003. Comparison of position of ANAT relative to MPLC between January and July, 2003 suggests about 19cm subsidence of the island. Horizontal displacement may not be significant though a few centimeters of offset toward north could be visible. Large subsidence may be due to the spouting of magma. In order to monitor the crustal deformation during the volcanic activity, we are continuing GPS tracking at the established two permanent sites for a while.

V32B-1016 1330h POSTER

Hydroacoustic Records of the First Historical Eruption of Anatahan Volcano, Mariana Islands

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For the past decade, NOAA/Pacific Marine Environmental Laboratory has monitored volcano-seismic activity from western Pacific island-arc volcanoes using an array of U.S. Navy hydrophones (called SOSUS) deployed at fixed locations throughout the North Pacific Ocean. SOSUS hydrophones are mounted within the SOFAR channel and record the hydroacoustic tertiary phase or T-wave of oceanic earthquakes from throughout the Pacific basin. Since acoustic T-waves obey cylindrical energy attenuation as opposed to the spherical attenuation of solid-earth seismic phases, sound channel hydrophones can detect often smaller and therefore more numerous earthquakes than land-based seismic networks. This property allowed for the detection of harmonic tremor from a submarine volcano in the Volcano Islands on hydrophones >14,000 km away in the eastern Pacific. The first historical eruption of Anatahan Volcano appears to have started (from satellite imagery) at 1730Z on 10 May, with an ash plume visible by 2232Z (BGVN, 5 May 2003). Records from a broadband seismometer deployed on nearby ($\sim$6.5 km) Sarigan Island indicate earthquake activity increased at about 1300Z on 10 May (D. Weins, pers com). SOSUS hydrophones in the western Pacific ($\sim$4000 km distant) also recorded increased earthquake activity at 1300Z on 10 May as well as continuous, low-frequency (<10 Hz) energy (possible volcanic tremor) that began about a day before the seismicity. The earthquakes and tremor were detected on only two SOSUS hydrophones and therefore it was not possible to estimate their source location. The arrival azimuth of the signals were, however, consistent with a source in the Mariana Islands. To complement the SOSUS hydrophone array coverage in the western Pacific Ocean, an array of five autonomous hydrophones were deployed in February 2003 (sponsored by NOAA's Ocean Exploration Program) within the SOFAR channel along the active island- and back-arc of the Mariana Islands. All five hydrophones (1-110 Hz bandpass) were deployed between 13°N and 22°N, with one hydrophone located within 50 km of Anatahan Island. These five hydrophone will be recovered in September 2003, and it is anticipated their data will provide insights into Anatahan, as well as Mariana Island wide, volcano-seismic activity.

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The Submarine Flanks of Anatahan Volcano

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The submarine flanks of Anatahan volcano were surveyed with EM300 multibeam sonar and the MR1 sidescan sonar from the R/V Thomas G. Thompson in February 2003. This was part of a larger survey of over 50 submarine volcanoes within the Marianas volcanic arc between 13°10'N and 23°10'N (see Embley et al. and Baker et al. abstracts, this meeting). This work was part of a multi-year study of seafloor volcanism in diverse tectonic settings, funded by NOAA's Office of Ocean Exploration. (see: http://oceanexplorer.noaa.gov/explorations/03fire/). The island of Anatahan has a maximum elevation of 798 m, but its submarine flanks descend to depths of 2000-2600 m, so most of the volcano lies below sea level. The submarine part of the volcano is elongated in the east-west direction, like the island. Conspicuous in the bathymetry are numerous small parasitic cones and hummocky ridges on the southwest and east submarine flanks of the island that radiate outward (downslope) from the island. These features appear as areas of high reflectivity in the MR1 sidescan sonar and some have distinctly lobate outlines, suggesting that they are areas of relatively young lava flows. Some of these lava flows extend up to 15 km from the coastline of the island and to depths below 2000 m. The upslope sources of these lavas are often ambiguous, but we interpret that they were erupted underwater (as opposed to erupted on land and then flowing into the ocean) because they are associated with cones and ridges that may be vent areas. The other flanks of the island appear to be draped in volcaniclastic material that has been transported downslope from the shoreline, in some cases as distinct flows that radiate outward in braided channels that have slightly higher reflectivity than surrounding areas in the sidescan imagery. These fragmental flows also extend to depths below 2000 m, especially on the west and south flanks of the island. The most prominent feature in the bathymetry around Anatahan is a submarine volcano located about 10 km NE of the island, here named NE Anatahan volcano. The summit of NE Anatahan volcano reaches a depth of 459 m, and the depth of the saddle between NE Anatahan and the submarine flank of Anatahan is 1000 m. NE Anatahan volcano has a circular crater rim that is open to the west. The summit and northern flank of NE Anatahan volcano are cut by normal faults that trend north-south, possibly reflecting the orientation of the local tectonic stress field. Another submarine volcanic construction is located 5 miles north of the island and is a linear ridge aligned in the NNW-SSE direction. This ridge has a crest at a depth of 1000 m, and the most recent deposits from Anatahan and NE Anatahan volcanoes are deflected around it. There is no evidence of any landslide materials on the submarine flanks of Anatahan, except perhaps for a small area southeast of NE Anatahan volcano. Even though there appears to be evidence for relatively young submarine eruptions at Anatahan, there has been no reported evidence for submarine volcanic activity during the 2003 eruption.

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Numerical Modeling of Sound from the Eruption of Anatahan Volcano, Mariana Islands

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NOAA VENTS Program deployed an array of five autonomous underwater hydrophones within the SOFAR channel along the Mariana chain in February 2003 to monitor seafloor volcanic eruptions and submarine earthquakes (sponsored by NOAA's Ocean Exploration Program). These five hydrophones will be recovered in September 2003 using KORDI *R/V Onnuri*. The first historical eruption of Anatahan volcano in the Mariana Islands began on 10 May 2003. It is expected that the hydrophone data will include the hydroacoustic records of the eruption of Anatahan Volcano. The signals recorded from the eruption will be numerically modeled using a T-wave excitation mechanism developed from the mode scattering theory of Park *et al.* (2001). They found that scattering from the rough seabottom converts the acoustic energy of seafloor earthquakes from the directly excited ocean crustal/water column modes to the propagating acoustic modes of T-waves, and developed an algorithm to numerically model oceanic earthquake's T-waves. We modified this numerical model of Park *et al.* (2001) to predict the T-waves generated from volcanic sources by adopting a buried magmatic pipe model (Chouet, 1985). We derived a moment-tensor representation of a volcano-seismic source that is governed by the geometry of the source and the physical properties of magma.

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Numerical modeling of the sound from the eruption requires us to determine governing factors such as the pipe radius and magma viscosity that will enable us to grasp the inward nature of Anatahan volcano.

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Seismic recording of the Anatahan eruption

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The first historic eruption of Anatahan volcano was fortuitously recorded by a broadband PASSCAL seismograph installed on the island only 4 days prior to the eruption. Although covered by ash during the eruption, the seismograph continued to operate throughout the main two month period of activity on Anatahan. This seismograph, located about 6 km west of the active eastern crater, as well as a seismograph installed on Sarigan about 45 km to the north, provide a continuous record of activity during the eruption. We have manually analyzed and visually picked arrivals from the 14 day period beginning 4 days prior to the eruption, and we have implemented an automatic event identification algorithm for the rest of the eruption period that has been calibrated relative to the manually processed data. In addition, we have located many of the larger volcano tectonic (VT) earthquakes using the P and S wave arrivals at Anatahan and Sarigan as well as P wave polarization data. Although these locations are not highly accurate they serve to delineate the general spatial progression of the earthquake activity. No earthquakes occurred in the crater region during the 4 days prior to the eruption. The only significant precursory earthquake activity was a swarm of events on May 8 that were located about 15 km northeast of the island and significantly deeper than events directly associated with the eruption. The first VT event from Anatahan itself was recorded at about 02:00 hrs GMT on May 10. The number of events per hour increases dramatically between 02:00 and 07:00 GMT. A period of nearly continuous earthquake activity commences at about 06:20 GMT which corresponds well with the eruption time of 07:30 GMT estimated by the Volcanic Ash Advisory Center from satellite photos of the ash cloud. After about 36 hours of intense earthquake activity, the number of discrete earthquakes declined, and were replaced by nearly continuous volcanic tremor. Much of the later part of the eruption was characterized by continuous volcanic tremor, probably associated with the dome building period of activity.

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The Anatahan volcano-monitoring system

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A real-time 24/7 Anatahan volcano-monitoring and eruption detection system is now operational. There had been no real-time seismic monitoring on Anatahan during the May 10, 2003 eruption because the single telemetered seismic station on Anatahan Island had failed. On May 25, staff from the Emergency Management Office (EMO) of the Commonwealth of the Northern Mariana Islands and the U. S. Geological Survey (USGS) established a replacement telemetered seismic station on Anatahan whose data were recorded on a drum recorder at the EMO on Saipan, 130 km to the south by June 5. In late June EMO and USGS staff installed a Glowworm seismic data acquisition system (Marso et al, 2003) at EMO and hardened the Anatahan telemetry links. The Glowworm system collects the telemetered seismic data from Anatahan and Saipan, places graphical display products on a webpage, and exports the seismic waveform data in real time to Glowworm systems at Hawaii Volcano Observatory and Cascades Volcano Observatory (CVO). In early July, a back-up telemetered seismic station was placed on Sarigan Island 40 km north of Anatahan, transmitting directly to the EMO on Saipan. Because there is currently no population on the island, at this time the principal hazard presented by Anatahan volcano would be air traffic disruption caused by possible erupted ash. The aircraft/ash hazard requires a monitoring program that focuses on eruption detection. The USGS currently provides 24/7 monitoring of Anatahan with a rotational seismic duty officer who carries a Pocket PC-cell phone combination that receives SMS text messages from the CVO Glowworm system when it detects large seismic signals. Upon receiving an SMS text message notification from the CVO Glowworm, the seismic duty officer can use the Pocket PC - cell phone to view a graphic of the seismic traces on the EMO Glowworm's webpage to determine if the seismic signal is eruption related. There have been no further eruptions since the monitoring system was installed, but regional tectonic earthquakes have provided frequent tests of the system. Reliance on a Pocket PC - cell phone requires that the seismic duty officer remain in an area with cell phone coverage. With this monitoring method, the USGS is able to provide rapid notice of an Anatahan eruption to the EMO and the Washington Volcano Ash Advisory Center. Reference Marso, J.N., Murray, T.L., Lockhart, A.B., Bryan, C.J., Glowworm: An extended PC-based Earthworm system for volcano monitoring. Abstracts, Cities On Volcanoes III, Hilo Hawaii, July 2003.

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Global Real-Time Volcano Hazard Monitoring with Satellites: The Anatahan Eruption

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On May 10, 2003, the island of Anatahan in the northern Mariana Islands experienced its first historical eruption. Anatahan is a 9 km long and 4 km wide island dominated by two volcanoes having E-W trending elongated and overlapping summit calderas. Following seismic activity in the 1990's, the island was largely evacuated. Thermal satellite data not only confirmed the eruption of the eastern crater of Anatahan but also pinpointed the location of continuing activity over a two-week period following the start of the eruption. These data were forwarded to hazard mitigation officials within hours of acquisition. NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) observes the Earth in the visible to infrared portion of the spectrum at 1 km x 1 km spatial resolution. Two MODIS instruments on Terra and Aqua provide global coverage 2-4 times per day, more towards higher latitudes. The Hawaii Institute of Geophysics and Planetology researchers developed an algorithm (MODVOLC) that mines the global Aqua and Terra data sets in order to pinpoint locations of volcanic activity. Currently, the time lag between data acquisition by MODIS and display on the web site is 2-4 hours. Weekly hotspot reports identify active volcanoes around the globe. Many volcanoes (Erebus, Heard, Anatahan, Michael) are in remote locations and otherwise would have gone unobserved or underobserved. The MODIS hotspot monitoring system provides reliable, and readily-accessible coverage of the world's volcanoes to support volcanic hazard mitigation efforts.

URL: http://modis.higp.hawaii.edu

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Anatahan, Northern Mariana Islands: Reconniassance Geological Observations During and After the Volcanic Crisis of Spring 1990, and Monitoring Prior to the May 2003 Eruption

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Anatahan island is an elongate strato volcano 9.5 km east-west by 3.5 km north-south. It is truncated by an elongate caldera (5 km east-west by 2.5 km north-south). The oldest rocks are andesitic and dacitic lavas and pyroclastics exposed on the outer flanks and caldera walls. These comprise the bulk of Anatahan, and include thick (∼10 m) and thin (2-3 m) plagioclase-porphyritic flows, well-indurated tuffs, and scoria units. On the steep north and south flanks of the volcano these rocks are cut by numerous ∼east-west oriented lineations of undetermined origin. Indurated breccias and a few lavas unconformably overlie scarps low on the flanks. Intermediate-age eruptive units include caldera-filling lavas and pyroclastics, and on the outer flanks eruptive vents and lava flows that filled erosional gullies. The youngest pre-2003 volcanic unit is a series of hydromagmatic pyroclastic surge and fall deposits. This unit is found over almost the entire island and in many places original depositional surfaces are preserved, often in high-energy environments, indicating a young (but undetermined) age. In March of 1990 increased local seismicity, a regional earthquake and reported increased fumarolic activity in the caldera prompted evacuation of Anatahan village, located at the W end of the island. Field investigations by the authors in April of 1990 to collect samples of rocks and fumarolic waters and to set up a geophysical monitoring network were inconclusive with respect to determining whether the activity was anomalous. Water samples were collected from bubbling muddy hot springs within the ∼1 km-diameter by ∼200 m-deep crater in the Eastern part of the caldera. Temperatures of near boiling and pH values as low as 0.75 were recorded in the field. A brief return visit in June of 1990 revealed that most of the water within the Eastern crater was gone although minor bubbling pools were observed. In the decade of the 1990s a more extensive seismic monitoring system was installed on the Northern Mariana Islands. Unfortunately, it had fallen into disrepair by the time of the May 2003 eruption and no precursory geophysical (or geological) data were available to indicate pre-eruption unrest.