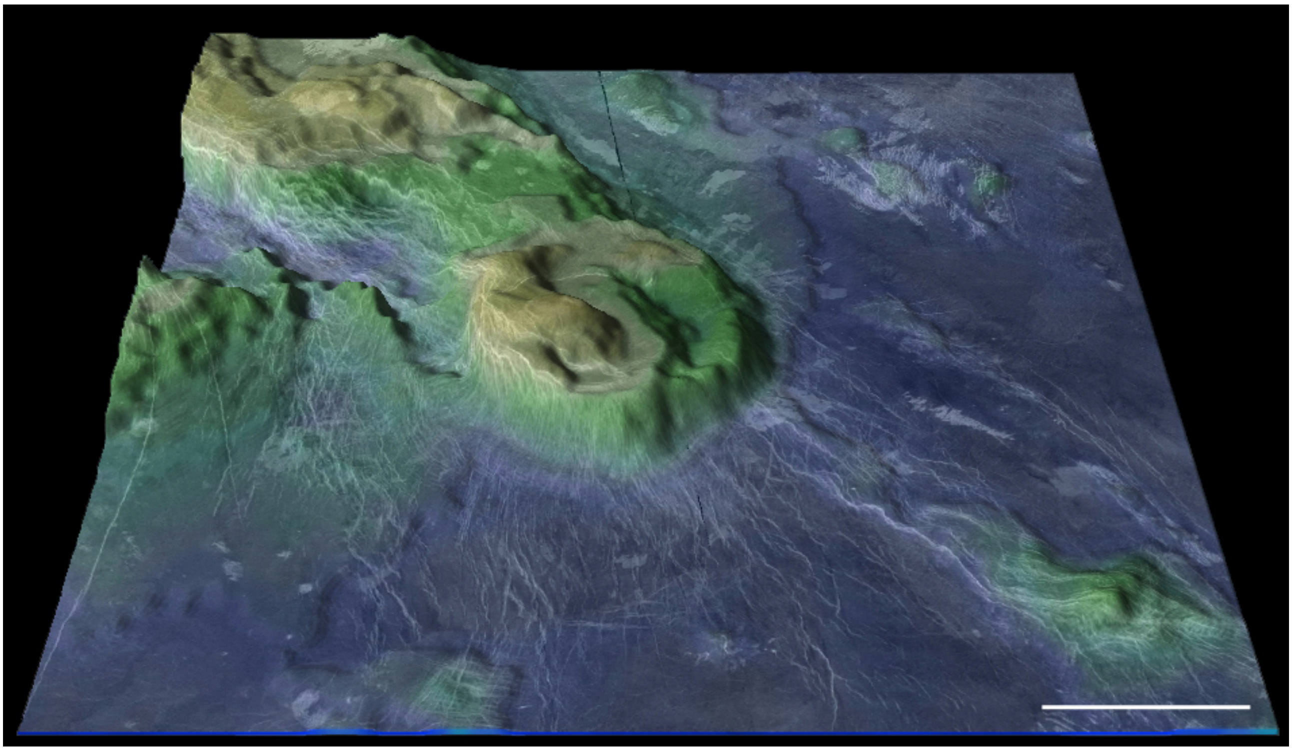
Planetary Volcanism

A Joint RAS 'G'/VMSG Meeting at
Geological Society Lecture Theatre, Burlington House, Piccadilly, London W1J 0BA.
Friday 14th November, 2003.

Convenors
Dr. Karl L. Mitchell (Lancaster University; k.l.mitchell@lancaster.ac.uk)
Dr. David A. Rothery (Open University; d.a.rothery@open.ac.uk)

The study of planetary surfaces in undergoing a renaissance, with new interplanetary missions being launched on a regular basis. The resolution and quality of data from these missions are now comparable with that of terrestrial products, and are released freely to the scientific community only a few months after acquisition. Our understanding is further improved by meteorite and lander-based geochemical studies. This meeting reflects the huge increase in activity and interest resulting from these advances. Presentations from UK and international scientists cover many aspects of planetary volcanism, including geo-/hydro-thermal studies.



3-D perspective image of Atai Mons, with Magellan SAR image and colour-coded topography overlain. Scale bar is approximately 100 km, vertical exaggeration is x10. Source: Grindrod, P. et al. "*The geology of Atai Mons, Venus: A volcano/corona hybrid*"

Directions to Burlington House

Located across the road from Fortnum and Mason, Burlington House is midway between Piccadilly Circus and Green Park underground stations, on the north side of Piccadilly. Burlington House surrounds a large courtyard which also houses The Royal Academy; after entering the gates you will find the Geological Society of London immediately on the right.

The nearest underground stations are Green Park or Piccadilly Circus. A schematic underground map can be found at: http://tube.tfl.gov.uk/content/tubemap/images/tm_quad_2h_0309.gif.

Bus numbers 9, 14, 19, 22 and 38 all stop near Burlington House. A local street map can be found at http://www.streetmap.co.uk/streetmap.dll?grid2map?X=529233&Y=180522&arrow=Y.

Programme

Note: time is very tight. Speakers are requested to keep within their time and to allow at least 3 minutes for questions (more for longer talks).

10:00 Registration and coffee

10:30 Morning session, chaired by Karl Mitchell
10:31 John Bridges (Open University): “*The SNC meteorites: information about basaltic igneous processes on Mars*”
10:48 Johannes Obenholzner (NHM Vienna): “*Volcanic aerosol particles on Earth: Can similar particles be found in extraterrestrial soil samples of planets or moons known for the existence of similar types of volcanism?*”
11:05 John Smellie (BAS): “*Sub-ice volcanism: hydraulics, edifice structures and implications for Mars examples*”
11:22 Daniel Mège (Universite Pierre et Marie Curie): "*Volcanic rifting at Martian grabens*"
11:52 Gerald Roberts (Birkbeck College London): “*Structural Evolution of Cerberus Fossae, Mars*”
12:09 Richard Ghail (Imperial College London): “*A general theory of plate tectonics*”
12:26 Ernst Hauber (DLR-Berlin): “*The topography and morphology of low shields in Tharsis, Mars*”
12:43 Ashley Seabrook (Open University): “*Small cones in Isidis Planitia – evidence for fracture controlled volcanism?*”

13:00 Lunch
Posters will be on display throughout lunch:
Louise Bishop (University College London): *“Geological mapping of Elysium, Mars”*
John Bridges (Open University): “*KREEP-rich cumulates in Lunar Meteorite NWA773*”
Peter Grindrod (University College London): “*The geology of Atai Mons, Venus: A volcano/corona hybrid*”
Mark Hake (Lancaster University): “*Emplacement of the Prometheus compound pahoehoe lava flow field on Io*”
David Heather (ESTEC, Netherlands): “*Volcanism on the Marius Hills Plateau on the Moon*”
Louise Norman (Lancaster University): “*Deducing the environmental and tectonic setting for volcanic activity around Elysium Mons, Mars*”
Alexis Rodriguez (University of Tokyo): “*Graben formation by igneous-tectonic induced terrain deflation in the Shalbatana northern region, Mars*”
Ken Thomson (University of Birmingham): “*Seismic volume visualisation: a new tool for understanding volcanism*”

14:00 Afternoon session, chaired by David Rothery
14:04 Karl Mitchell (Lancaster University): “*Late stage volcanism at Olympus Mons*”
14:21 Laszlo Keszthelyi (USGS Flagstaff): "*Flood Lavas on Earth, Io, and Mars*"
14:51 John Guest (University College London): “*Evolution of the Venusian volcanic plains*”

15:30 Tea

16:00 Ordinary meeting of the RAS (Free admission)
Talks include: Lionel Wilson (Lancaster): “*Recent volcano-cryosphere-hydrosphere interactions on Mars*”

18:00 Drinks reception

19:00 Close

Admission

Admission to the meeting is free to all RAS and GSL members upon proof of membership. £10 is charged to non-members (£5 to students), collected on the door. We would particularly like to encourage terrestrial volcanologists to attend as cross-over between terrestrial and extraterrestrial communities has often been poor. To that end, the attendance fee for non-GSL VMSG members can also be waived if you contact Karl Mitchell in advance. Admission fees may be offset against RAS membership fees for those joining on the day.

Special publication

We will also be accepting full papers for a GeolSoc special publication after the meeting (not obligatory for meeting contributors). If you would like to contribute a paper, or require more information, please e-mail Karl Mitchell.

Geological Mapping of Elysium , Mars

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Images of the surface of Mars obtained by the Viking mission have been used in conjunction with images and topography data from the Mars Global Surveyor (MGS) mission to further our understanding of the geology of the region around Elysium Mons. Images from the Mars Orbiter Camera (MOC) onboard MGS have allowed the analysis of small surface features and textures, and have highlighted the fact that there has been much modification of lava flows and other features by the action of both wind and fluid flow (possibly of water or a water/mud mixture). Some potential periglacial features have also been observed.

Analysis of topography data from the Mars Orbiter Laser Altimeter (MOLA) onboard MGS, has greatly altered our views on the history of the area. From digital elevation models and contour maps produced using MOLA data, it appears that Elysium Mons may be the result of a shift in vent activity for a much larger ancient volcanic edifice, and thus was emplaced on top of the older volcano. Hecates Tholus may have been active at the same time as this larger edifice, but once activity at Hecates Tholus ceased it became surrounded and embayed by flows from the larger edifice.

Topography data also show that first lava, and then a second fluid (probably water) was erupted from the Elysium Fossae, and that eruption of these materials occurred from the base of the larger volcanic edifice. There appear to have been several eruption episodes of water or water/mud from the fossae as several different layers within the erupted materials can be observed on shaded MOLA maps.

Analyses of the dimensions of lava flows in this area have been used to produce eruption durations for individual flows, and thus allow the calculation of effusion rates. Average effusion rates for flows from Elysium Mons have been calculated to be between 0.5×10^3 and 10.7×10^3 $m^3.s^{-1}$. This is slower than effusion rates calculated in the same way for lava flows on the volcano Alba Patera (which is in a completely different area of Mars) and may imply that there are differences in composition or eruption mechanism of lavas in the two areas. MOLA data also enabled the production of longitudinal lava flow profiles, which helped to constrain the ways in which lava flows in Elysium were emplaced. This analysis of lava flows could be used to characterise some of the units in our mapping area.

KREEP-rich cumulates in Lunar Meteorite NWA773

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There are currently 27 lunar meteorites providing a range of Mare and Highlands material for study. Here I report on work conducted on a lunar regolith meteorite which contains evidence for cumulate processes underlying a Mare setting [Bridges J. C., Jeffries T. E. and Moncrieff C. Olivine-rich Clasts and Symplectite-bearing Breccia in KREEP-bearing Lunar Meteorite NWA773. Geochim. Cosmochim. Acta (subm.)].

NWA773 contains approximately 38% of a feldspathic peridotite, 3% urKREEP, 53% low Al-K, silica-oversaturated VLT (Very Low Ti) basalt. The proportions of the VLT, urKREEP and peridotite were derived from a Least Squares Mixing Program. The feldspathic peridotite is one the most primitive lunar samples identified and has bulk Mg# = 70 and 55-66 vol.% olivine. However it has a KREEP geochemistry associated with the presence of minor apatite and orthoclase. Within the breccia we have identified green VLT glass/microcrystalline pyroxene clasts and fa+orth+silica symplectites. The latter formed from the breakdown of pyroferroite due to heating at 1000-1200°C for several days. Anorthite+Al-rich pyroxene symplectites are also present. Some fa+orth+silica symplectites are found at the margins of peridotite clasts suggesting that their high temperature formation may have been proximal to and at the same time as the peridotite was intruded or mixed into the regolith components. Equilibration of pyroxene ($En_{37\text{-}54}Fs_{12\text{-}28}Wo_{29\text{-}40}$ and $En_{37\text{-}54}Fs_{21\text{-}27}Wo_{5\text{-}18}$) and olivine ($Fo_{70\text{-}71.4}$) occurred within the peridotite lithology. In contrast, pyroxene grains within the breccia have a wide range of compositions $Wo_{7\text{-}30}$ $Fs_{19\text{-}60}$ and $Al_2O_3 \leq 10$ wt%. The feldspathic peridotite has ≈ 0.05 x KREEP abundances of the REE and the breccia is ≈ 0.1 x KREEP. The REE abundances (LA-ICPMS) of peridotite minerals are consistent with formation from a KREEP melt. The green VLT glass in the breccia has 10 – 20 x CI, La/Lu = 1.2, Eu/Eu* = 0.5.

We suggest the feldspathic peridotite formed through limited fractionation of a KREEP basalt, followed by the addition of trapped KREEP liquid ($\approx$5%) to peridotite adcumulates. This model has previously been applied to Highland Mg-suite samples and the feldspathic peridotite has geochemical features ie primitive pyroxene and plagioclase compositions together with KREEP geochemistry, akin to them. This suggests that the NWA773 peridotite formed through similar fractionation and cumulate processes to the Mg-suite but that it occurred in a Mare, VLT-dominated setting. The NWA773 breccia gained its urKREEP component through melt percolation and crystallisation of a REE-rich apatite.

The SNC meteorites: information about basaltic igneous processes on Mars

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There are currently 28 known SNC (martian) meteorites and they fall into 4 main groups: the Shergottites, Nakhlites, Chassignite (a dunite) and ALH84001, which is an orthopyroxenite. The 20 shergottites are subdivided into basaltic and lherzolitic subgroups. Most of the shergottites are cumulates or mixtures of mafic xenocrysts and basaltic melt. The basaltic shergottites have high Fe/Mg+Fe ratios (0.5-0.75), low Al_2O_3 contents (5-12 wt%) and have higher moderately volatile element contents compared to terrestrial basalts reflecting the inferred chemical abundances within the Martian mantle source region for the melts. The 6 nakhlites are ol-bearing clinopyroxenite cumulates which formed from a LREE-enriched basalt through adcumulus growth with some (<10%) trapped melt [1]. Abundances of highly siderophile elements (e.g. Ir) in SNCs are comparable to typical terrestrial mafic-ultramafic abundances [2]. These data suggest that after Mars' core formation, the mantle was enriched by 'late veneer' accretion.

The mineral assemblages in SNCs are consistent with crystallisation at fO_2 close to the QFM buffer and are virtually anhydrous although significant quantities of water and CO_2 are associated with secondary mineral assemblages formed by the evaporation of low-temperature brines in events not associated with crystallisation of the parent rocks [3].

The basaltic shergottites probably crystallised within large flood lava flows entraining some plutonic lherzolite. Nakhlites crystallised within thick (~100m) flows or sills. Both the TES results from Mars Global Surveyor and the Pathfinder soil and rock analyses suggest that the basaltic shergottite composition is a major component of the Martian surface, although a more K-rich andesitic component is inferred to also be present in the northern plains [4].

The SNCs have crystallisation ages, determined with a variety of techniques, ranging from 1.3 - 0.17 Gyr and one (ALH84001) crystallised 4.5 Gyr [5]. The younger SNC meteorites correspond to the Amazonian System (approximately <2.9 Ga, [6]) and ALH84001 is our only sample of Noachian crust. No Hesperian age samples have been identified therefore our samples are biased towards younger igneous rocks from the northern plains and Tharsis region. The variation in whole rock REE, Sm-Nd data for SNCs [5], suggests that the parental melts derived from depleted mantle source regions assimilated crustal components that were LREE-enriched with lower $^{143}Nd/^{144}Nd$ ratios.

It has been determined through Cosmic Ray Exposure ages that the SNC meteorites were ejected from these regions in 5-8 different events over the last 20 My [5]. The presence of young crystallisation ages is consistent with crater counting in suggesting that Martian volcanism has essentially continued until the present day.

References: [1] Bridges J. C. et al. (2003) *Meteorit. Planet. Sci. 38*, A119. [2] Warren P. H et al. (1999) *Geochim. Cosmochim. Acta 63*, 2105-2122. [3] Bridges J.C. et al. (2000) In *Chronology and Evolution of Mars*, (eds. Kallanbach R. et al.) Kluwer, p365-392. [4] Bandfield J. et al. (2000) *Science 287*, 1626-1630. [5] Nyquist L.E. et al. (2000), In *Chronology and Evolution of Mars*, (eds. Kallanbach R. et al.) Kluwer, p105-164. [6] Hartmann W.K. and Neukum G. (2000) 165-194, In *Chronology and Evolution of Mars*, (eds. Kallanbach R. et al.) Kluwer, p165-194.

A General Theory of Plate Tectonics

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The theory of plate tectonics has revolutionised our understanding of the geology of the Earth; we now know that it is the dominant cause of and control on terrestrial volcanism. Notwithstanding its success at explaining the observed geology of the oceans, it has never fully explained the behaviour of the continents, in the main treating them as a passive component in the global tectonic framework. Moreover, did plate tectonics operate on the early Earth? Conditions then were significantly different to the present; the heat flow is estimated to have been at least a factor of two or three greater than at present and the mantle nearly 200K hotter. Moreover, there is a debate about the geological evidence, between proponents of a plate tectonic model of Arch¾an terrains, and others who argue for a plume model or other alternatives.

Mars is the smallest independent terrestrial body with evidence of large-scale tectonism, principally the Vallis Marineris rift. However, there is no strong evidence that Mars ever broke down its lithosphere into a number of plates and it is perhaps best to consider Mars the largest of the "one-plate" small planets. In contrast, Venus displays abundant evidence of plate behaviour, with numerous rift zones, mountain belts and strike-slip systems. Nonetheless, there is also strong evidence that Venus underwent at least one episode of rapid, predominantly volcanic, near-global resurfacing. Although not widely recognised as such, Earth also underwent similar episodes (referred to as "super-plume" events), usually in association with the breakup of supercontinents. Earth can, in itself, be considered to operate a "dual-mode" of plate tectonics, one in its oceans and another in its continents. Earlier on in its history (the first 2 Ga), Earth may have been more similar to Venus now, with just one mode of plate tectonics operating.

Io is better known for its volcanism but it does have significant non-volcanic mountains and there is indirect evidence for rapid plate movement. Io's rate of heat loss is extreme and provides a model of the super-plume or near-global resurfacing episodes inferred on Venus and Earth. Ganymede, on the other hand, has clear evidence of once-mobile plates but no evidence of volcanism. Its lithosphere is essentially water ice and might, therefore, be expected to behave differently to the terrestrial planets; however, these differences are likely to be more of form than substance.

It is therefore compelling to conclude that the currently accepted theory of plate tectonics, proposed to explain geological observations from the oceans, is a special case, in that it applies only to negatively buoyant lithospheres, of which the oceanic lithosphere is the only known example. A general theory of plate tectonics, applicable to all lithospheres (which are, in the main, positively buoyant), is required. Such a theory is a natural extension of the treatment of all planets as geological heat engines and represents an integral part of our understanding of the role of volcanism on terrestrial planets.

The Geology of Atai Mons, Venus: A Volcano/Corona 'Hybrid'

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The Magellan mission to Venus revealed a surface upon which volcanic features, including large volcanoes and coronae, were prevalent. Large volcanoes are defined as volcanic centres with diameters ≥ 100 km, which are dominated by radial flows and positive topography. Coronae are volcano-tectonic structures that have a wide range of morphologies, are thought to be the surface manifestation of buoyant mantle diapirs, and are apparently unique to the surface of Venus. Some features on Venus (herein referred to as 'hybrids') show characteristics typical of both large volcanoes and coronae suggesting similar formation processes and/or conditions. This abstract details part of our ongoing investigation into these hybrids to develop a better understanding of the relationship between large volcanoes and coronae.

Atai Mons is classified by the United States Geological Survey (USGS) as a large volcano, but demonstrates some features that are indicative of coronae. It lies at -22°N, 291°E, in south-eastern Phoebe Regio, about 1.7 km above the surrounding plains (Fig. 1). It has a sub-circular lava flow apron, similar to that of many large volcanoes on Venus, with an average diameter of ~ 400 km and a surface area of approximately 1000 km^2. The lava apron is made up almost entirely of digitate flows, which originate from flank vents. Atai has a topographic profile that is similar to many coronae, with relatively steep outer slopes and a partial topographic rim giving a summit depression of about 100 km in diameter. This summit region has been flooded by radar-dark (smooth) volcanic material. Tectonism at Atai can be split into three main groups: closely-spaced radial fractures, concentric graben, and Pinga Chasma related fractures. The radial fractures orientate away from the centre of Atai, only occur on and away from the topographic rim and have not been deflected by Pinga tectonism. The concentric fractures appear to postdate the radial fractures, occur further away from the topographic rim and show some signs of deflection by Pinga-related fracturing. The tectonism associated with Pinga Chasma occurs in a well-defined NW-SE trend, and is seen to have occurred after the radial fracturing but concurrent with and subsequent to the concentric fracturing.

Detailed analysis of superposition relationships at Atai Mons reveals the following sequence of events: formation of original plains material; uplift and associated radial fracturing and lava flows at Atai; gravitational relaxation causing broad a summit depression and exterior concentric fracturing; volcanic flooding of summit depression; localised summit collapse causing caldera-like interior concentric fracturing; extension associated with Pinga Chasma; summit flooding and building of small central volcano. The extensive volcanism and radial tectonism are typical of large volcanoes on Venus, but the concentric fractures and broad summit depression are evidence for a large-scale downwelling phase similar to that observed at many coronae. Atai Mons could therefore be interpreted as a corona that has become more volcano-like during its history. This geological history represents only the currently visible part of the evolution of Atai Mons, but nonetheless demonstrates processes that are mutual to both large volcanoes and coronae on Venus.

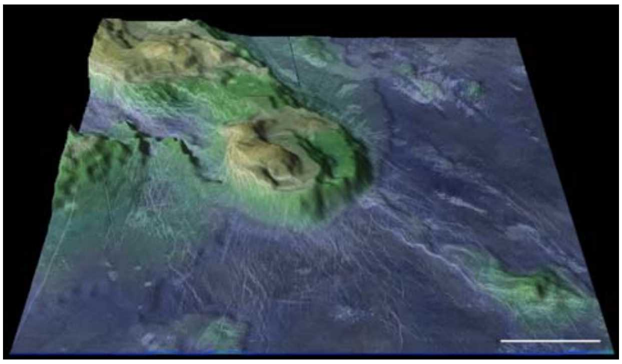

Fig. 1: 3-D perspective image of Atai Mons, with Magellan SAR image and colour-coded topography overlain. Scale bar is approximately 100 km, vertical exaggeration is x10.

Evolution of the Venusian Volcanic Plains

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The plains of Venus, which make up most of the surface of the planet show wide range of styles of volcanism which have contributed to their formation, including extensive lava flow fields from fissure sources, fields of hundreds of small edifices each in the order of 10 km across, flows associated with major rifts and flow fields from coronae.

We have examined quantitatively the contribution of these different sources to plains formation. Our conclusion is that the plains of Venus have complex history with repeated styles of activity, implying a non-directional evolution of Venus as represented in the surface strata. We also recognise that, while SAR images have much to offer in terms of recognising surface textures, it has severe limitations for the recognition of individual geological units, and extensive, apparently continuous geological units, may represent numerous rock units produced at different times.

Emplacement of the Prometheus compound pahoehoe lava flow field on Io

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Io is the most volcanically active body in the Solar System and presents the first clear evidence of ultrabasic volcanism since the eruption of komatiite lavas on ancient Earth. Eruptive lava temperatures up to ~1700–2000 K are consistent with ultramafic silicate volcanism analogous to that which produced ancient terrestrial komatiite lavas and large volume flood basalts. Such lavas have very small dynamic viscosities (~0.3 Pa s) and negligible yield strengths on eruption. The voluminous Ionian compound lava flows, such as the ~10 m thick, ~200 km long Prometheus flow field, are composed of thermally-efficient, complex and continuous tube-fed plumbing systems. They contain individual lava flow units that are typically a few hundred meters long, probably ~0.1-1 m thick, and have their lateral extents limited by cooling. The Ionian pahoehoe style flows illustrate complex sequences of interfingering and overlapping flow units, displaying slow, laminar, radial flow front advance by budding and breakout of individual lobes and toes, and probably also involve inflation. This flow emplacement mechanism on Io is similar, apart from the increased spatial scale, largely caused by the smaller acceleration due to gravity on Io, to that which commonly operates on the flanks of Kilauea, Hawai'i. Here we attempt to estimate the effusion rates and thicknesses of individual lava breakouts.

The Prometheus flow commences by overspill and a westerly free-flow from the partly crusted-over lava lake at the Prometheus caldera, with motion in narrow lava channels on a plausibly steeper slope dominating. Widening and branching of the flow indicating more gentle topography governs the rest of the flow emplacement, except for the possible topographic control and narrowing of the flow in the middle, ahead of the final major compound flow field emplaced on near-horizontal topography. Estimates of the thickness of the Prometheus flow field, imaged at high resolution by Galileo, are 10-30 m. Given its total length of ~200 km and average width of ~30 km, its volume must be ~120 km^3.

The flow field was emplaced during the 17 years between the Voyager (1979) and Galileo (1996) missions, which sets a lower limit on the mean magma supply rate to the entire flow field of 220 m^3 s^{-1}. Changes in length seen during the Galileo mission may imply a mean rate up to twice this value. There is a dramatic increase in breakout frequency (low-albedo patches in Figures 1-3) with increasing distance along the flow from the caldera. On the assumption that the albedo of breakout material decreases with time as it gets cooler and eventually becomes progressively more thickly coated with SO_2 frost from active vents, the fact that there are ~30 distinct low-albedo patches suggests that about this number of breakouts are active at any one time. Then given the above estimate of a 200-400 m^3 s^{-1} effusion rate for the entire flow field, the typical effusion rate at each breakout can be estimated as ~10 ± 4 m^3 s^{-1}.

The topography and morphology of low shields in Tharsis, Mars

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The Tempe Volcanic Province (TVP) on Mars (~80°–90°W and ~30°–40°N) is characterized by low shields, cones, sheet flows, pit craters, maars, and linear depressions like rift zones and grabens [1,2]. We investigate its topography, morphology, and age using Mars Orbiter Laser Altimeter (MOLA), Viking Orbiter image (VO), Mars Orbiter Camera (MOC), and Thermal Emission Imaging System (Themis) data. In particular, the characteristic small and very low shield volcanoes of the TVP can be investigated in more detail with MOLA data than it was previously possible with indirect topographic information derived from Viking imagery (shadows, photoclinometry). Our morphometric measurements confirm earlier, VO-based suggestions [3] that the TVP is directly comparable to terrestrial *plains volcanism* as observed in the Snake River Plains (Idaho) [4,5]. In addition, we find surface features (lava tunnels or tubes, sinuous rilles, and possibly cinder cones), which have not been noted in the TVP before. Our new crater counts indicate an absolute age of the lava flows of ~1.1–0.5 Ga. We also compare the TVP to other regions in Tharsis where large numbers of small and very low shields are concentrated (Ceraunius Fossae, SE flank of Pavonis Mons, Syria Planum). In contrast to other reports [6,7], we do not find any latitude-dependent variations in the morphology of the low shields. Therefore, we do not agree to the conclusions of [6,7] that the morphology of the shields is controlled by the latitude-dependent distribution of subsurface volatiles. Instead, we find the morphology of the shields to be identical everywhere in Tharsis. Low viscosity basaltic lavas and very high eruption rates seem to be indicated from the association of shields with shallow slopes (low viscosities) and sinuous rilles (known to indicate high eruption rates on the Moon [e.g., 8,9]). A high Fe-content of the parent magma together with the specific Martian environment (e.g., thin atmosphere, low gravity; see [10]) may be responsible for the low viscosities and the extremely shallow flank slopes of the shields, which are – to our knowledge - the shallowest in the solar system.

References: [1] Hodges C. A. (1979) *NASA Tech. Memo. 80339*, 247-249. [2] Hodges C. A. (1980) *NASA Tech. Memo. 81776*, 181-183. [3] Plescia J. B. (1981) *Icarus, 45*, 586-601. [4] Greeley R. (1977) *NASA CR-154621*, 23-44. [5] Greeley R. (1982) *JGR 87*, 2705-2712. [6] Sakimoto S. E. H. et al. (2003a) *LPS XXXIV*, abstract #1740. [7] Sakimoto S. E. H. et al. (2003b) *6th Int. Conf. Mars*, abstract #3197. [8] Wilson, L. and Head, J. W. (1980) *LPS* XI, 1260-1262. [9] Head, J. W. and Wilson, L. (1980) *LPS* XI, 426-428. [10] Wilson, L. and Head, J. W. (1994) *Rev. Geophys. 32*, 221-263.

Volcanism on the Marius Hills Plateau on the Moon

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The lunar Marius Hills region comprises a plateau with an area of approximately 35000km^2 (Greeley 1971, Whitford-Stark and Head 1977) rising several hundred metres from the surrounding plains of Oceanus Procellarum (McCauley 1967). The mare flows in the region are predominantly Eratosthenian in age, although volcanic activity on the plateau is thought to have extended from the Imbrian through to the Eratosthenian period (McCauley 1967, Whitford-Stark and Head 1980). The plateau contains the highest concentration of volcanic structures in Oceanus Procellarum, including low domes, steep sided domes, cones and rilles (McCauley 1967, Greeley 1971, Guest 1971, Whitford-Stark and Head 1977).

We have studied the lunar Marius Hills region and mapped the spectrally distinct flows present for the first time, using photographic and Clementine multispectral data. We find that the basalts on the Marius Hills plateau are varied in age and composition but are dominated by a high-titanium Erathosthenian basalt, most likely from the same source as the Flamsteed Basalt, further south. The thickness of the basalts across the plateau is consistently greater than 120m and is considerably thicker in some areas. A lower limit of 5320km^3 of basalts has been erupted onto the plateau. The domes and cones in the region do not appear to be related to any specific basalt or volcanic episode but occur at all levels in the stratigraphy that can be derived in the region. The eruption conditions required to form these constructs indicate that they must represent a series of separate volcanic episodes occurring throughout the history of the plateau. Cones of the Marius plateau are dominated by a strong glassy signature and often have an associated microlitic structure. Examples are shown of localised microlitic or glassy materials in regions where no cone construct is evident in the photographic data. These features are proposed to represent short-lived pyroclastic episodes that have deposited glassy and microlitic units on the plateau but have not been maintained for long enough to develop a cone. The volcanic history of the Marius Hills region is extremely complex, and most likely involved several separate episodes of volcanism with a large contrast in eruption styles and characteristics. See Heather, Dunkin & Wilson (2003) for further details.

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Flood Lavas on Earth, Io, and Mars

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Flood lavas are major geologic features on all the major rocky planetary bodies. They provide important insight into the dynamics and chemistry of the interior of these bodies. On the Earth, they appear to be associated with major and mass extinction events. It is therefore not surprising that there has been significant research on flood lavas in the recent years.

One of the more contentious debates in physical volcanology has centred on the manner in which flood basalt lavas are emplaced. The pioneering work of Shaw and Swanson (1970) suggested eruption durations of days and volumetric fluxes of order 10^6 m^3/s. The flows would have moved as turbulent floods. However, our understanding of how lava flows can be emplaced under an insulating crust was revolutionised by the observations of actively inflating pahohoe flows in Hawaii by Hon et al (1994). These new ideas led to the hypothesis that flood lavas were emplaced over many years with eruption rates of order 10^4 m^3/s (e.g., Self et al., 1996, 1997, 1998). The field evidence provides overwhelming support that at least one example in the Columbia River Basalts was emplaced as an inflated pahoehoe sheet flow over a period of about a decade (Thordarson and Self, 1998). There is similar field evidence that inflated pahoehoe sheet flows are to be found in continental flood basalt provinces including the Deccan Traps, Etendeka lavas, Kerguelen Plateau (e.g., Keszthelyi et al., 1999; Jerram, 2002; Keszthelyi, 2002), as well as other long basaltic lava flows across the globe. This led to the hypothesis that the "Standard Way of Emplacing Long Lavas" (SWELL) was as inflated pahoehoe sheet flows (Self et al., 1998). This was reinforced by the observation of ≥100-km-long active lava flows on Io being formed as compound sheet flows fed by moderate eruption rates (10^2-10^3 m^3/s) (McEwen et al., 2000; Keszthelyi et al., 2001).

While it is observable fact that many long lava flows are inflated pahoehoe sheet flows, ongoing research has found that it is not the only way that long lava flows are emplaced. The first clue came from Mars, where new high-resolution images of remarkably fresh flood lavas revealed a morphology uncommon on Earth (Fig. 1), dubbed "platy-ridged" lava because it was dominated by large rafted plates and ridges formed by compression of the flow top (Keszthelyi et al., 2000). Other puzzling features included large shear zones and wakes cut into the flow top. A search for appropriate terrestrial analogs found two examples in Iceland: the 1783-1784 Laki Flow Field (Fig. 2) and the Burfells Lava near Krafla. A detailed examination of these flows showed that they posses a strange mixture of 'a'ā and pahoehoe characteristics. The brecciated flow tops consisted of pieces of pahoehoe, not 'a'ā clinker, leading us to call this "rubbly pahoehoe." There was also evidence of significant inflation of these lavas. We have found similar flows in the Columbia River Basalts and the Kerguelen Plateau.

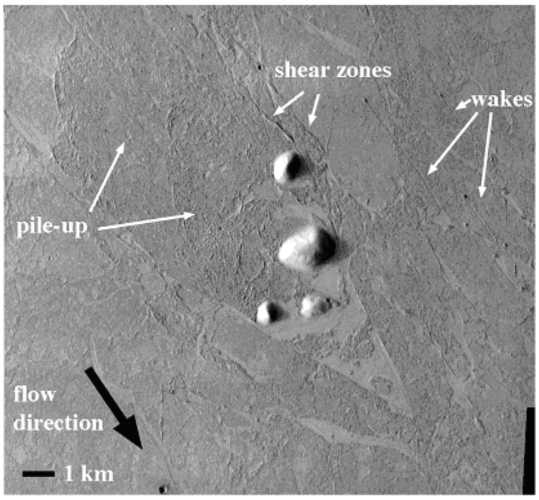

Fig. 1: THEMIS image V06012001, Cerberus Plains, Mars.

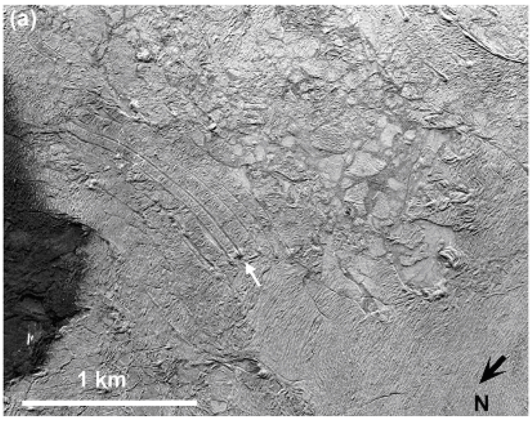

Fig. 2: Air photo from Laki Flow Field, Iceland.

We hypothesise that these flows form with a thick, insulating, but mobile crust, which is mobilised when the volumetric flux is too large to remain in the normal pahoehoe mode of emplacement. This is supported by the observation of platy-ridged lava morphology on the surface of the most rapidly emplaced large lava flow seen on Io.

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Volcanic rifting on Mars

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Lava plains and plateaux are widespread on Mars but many of them were apparently not erupted from central volcanoes. In this contribution, we suggest that some of them may have emplaced from fissure swarms, whose eruption triggered surface collapse along rift zones (figure 1).

Volcanic landforms aligned with many Martian grabens, mainly collapse features, suggest that tectonic stretching has occurred simultaneous to crustal dilation by magma emplacement parallel to the grabens. Observational evidence and comparison with volcanic rifts on Earth suggest a scenario of rifting in which tectonic stretching at surface is balanced by magma emplacement at depth. A series of scaled experimental models of rifting simultaneous to magma withdrawal in a reservoir underneath a graben was performed in order to better understand the relationships between magmatic and tectonic processes. The models show that magma withdrawal can explain the formation of the collapse features within the grabens. Graben border faults may even form in response to magma withdrawal solely, without any contribution of a strongly deviatoric remote extensional stress field. In some instances, the depth and width of the magma reservoir can be inferred from the geometry of the fractures and collapse features at surface. Graben geometry can also be used to constrain crustal rheology.

The large size of some collapse features, their distribution along the rift zones, the results of the experimental models, as well as limitations on instantaneous rock stretching provided by rock strength and confined boundary conditions imposed by the absence of plate tectonics, makes it unlikely a process of collapse above single, very thick dykes. More likely is a process of collapse above the deflated magma reservoirs after the eruption of reservoir-fed fissure swarms.

Therefore, similar to terrestrial rift zones, every rift zone may have its own fissure swarm. The general pattern in the Tharsis region may be that of a swarm of grabens located above a swarm of magma reservoirs giving birth to a swarm of fissure swarms.

Due to the absence of plate tectonics, the maximum expansion along the rift zones depends on the magnitude of the crustal uplift accompanying the magmatic activity, which dictates the space made available for magma intrusion. Oceanic-type spreading may have occurred on Mars along the grabens displaying evidence of associated volcanic activity, but due to this constraint, only a limited number of spreading events could have occurred at each rift zone.

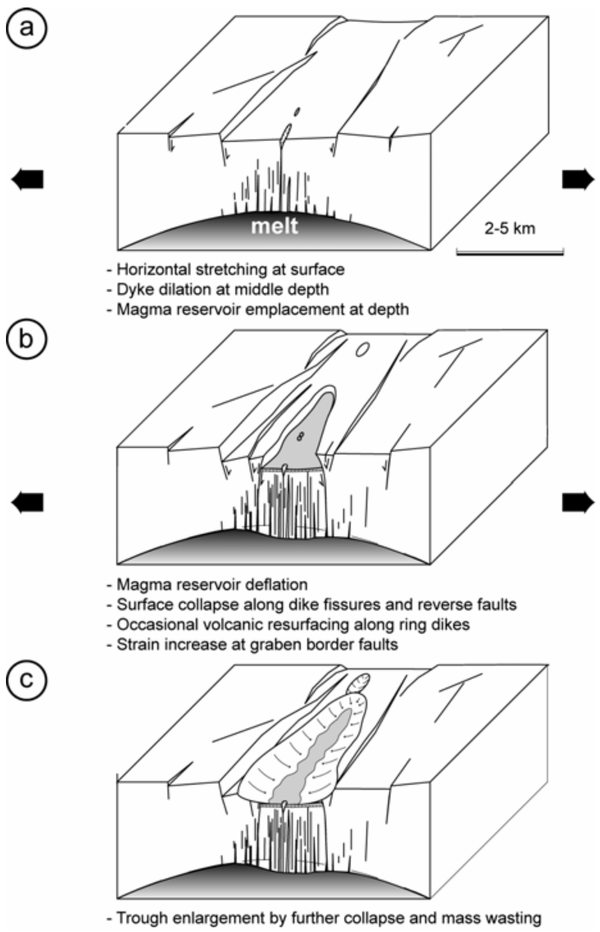

Fig. 1: Morphostructural evolution of a Martian rift zone.

Late stage activity at Olympus Mons, Mars

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Previous workers [1] have suggested that the flanks of Olympus Mons are characterised by channelised lava flows with morphologies similar to 'a'a, overlapping to produce an overall "feathery" texture. High resolution imagery of the slopes of Olympus Mons from Mars Global Surveyor and Mars Odyssey has revealed copious (many thousands of) parallel-sided ridges. We infer that these are leveed volcanic flows, based on their location, radial orientation and morphological characteristics. They range up to many hundreds of km in length, tens to a few hundred m in width and up to ~120 m in thickness. Occasional sinuous channels (sometimes with source depressions), interpreted as being either collapsed lava tubes of due to thermal erosion, are interspersed with the leveed flows; they tend towards occupying higher elevations, suggesting a possible causative relationship. Most leveed flows emanate from elevations 8 km (vertically) below the summit or lower, but no clear sources have been identified. Many continue to the escarpment, but rarely do they continue more than a few kilometres beyond with the same morphology. In places the leveed flows appear to transform into more sheet-like flows or vice-versa, often with one sheet-like flow associated with many ridge pairs.

We have investigated multiple hypotheses for the origin of these ridges, and favour an interpretation as leveed lava flows, erupted from laterally propagated dykes. Such flows on the Earth can be the result of a broad spectrum of magma chemistries, but steeper leveed flows are typically associated with more silicic (and hence viscous) mineralogies, typically andesitic or dacitic, than we expect on Mars. However, long lava flows are generally associated with hot and less viscous lavas, such as basalts, and although not inconsistent with more silicic magmas if effusion rates are large [2], such activity seems unlikely on Mars as more silicic magmas will also tend towards explosive activity. We have also found that up-slope the levees tend to be shallower at the proximal end of the flow, and steeper at the distal end, which is interpreted to be cooling limited in many cases, suggesting that the steeper levees are caused by a progressive increase in yield strength, probably due to progressive cooling.

The slopes of Olympus Mons are of Upper Amazonian age, and so these features are among the youngest products of volcanism on Mars. Following a global survey, we cautiously interpret only a handful of similar features on Ascraeus Mons, Elysium Mons and to the east of Apollinaris Patera as being possibly similar in origin - and in no cases are they as well preserved or as numerous as those on Olympus Mons. The lack of similar features on other Martian volcanoes may be because they are representative of a style of activity that is rare elsewhere, possibly due to this being late stage volcanism, or because they are heavily degraded due to relative age or greater erosion rates. The young age implied by stratigraphy and inferred from recent revisions to crater count statistics is consistent with suggestions [3,4] that Mars, and Olympus Mons in particular, is in a period of volcanic dormancy.

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Deducing the Environmental and Tectonic Setting for Volcanic Activity around Elysium Mons, Mars.

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Analysis of a number of lava flow deposits to the north and north-west of Elysium Mons, Mars, together with inclusion of work by other researchers provides evidence of differing types of volcanic activity. It is evident that both explosive and effusive volcanism has occurred in this area of Mars in the past. In addition some morphologies and numerical results suggest the influence of water on the type of volcanism present.

Evidence for explosive activity at Hecates Tholus is present in past research papers. By contrast my recent study of Elysium Mons suggests a more effusive nature. The reason for this contrast between two closely situated volcanoes is put down to either the presence of subsurface water or a changing tectonic setting.

Effusive activity is evident through the presence of numerous lava flow deposits. These deposits include a large compound flow field, segmented flows, isolated flows and lava tubes. Examination of this range of deposit morphologies suggests differing local environmental conditions as well as differing magma sources.

A variety of methodologies were used in this study of the Elysium lava flow deposits and this highlights correlations as well as inconsistencies between models. Theories for particular deposit morphologies suggested by other researchers were also compared with my new analysis.

Volcanic aerosol particles on Earth: Can similar particles be found in extraterrestrial soil samples of planets or moons known for the existence of similar types of volcanism?

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High resolution FESEM/EDS studies of aerosol particles collected in volcanic plumes and fumaroles on Earth comprise a wide variety of particles in the sub-µm to µm range [1]. Explosive volcanism produces glassy, rock and magmatic mineral fragments. Condensates and sublimates of gases can create minerals and mineraloids, whereupon most of them are thermodynamically unstable. Catalytic reactions between elements transported by the gas phase and i.e. Si-rich substrata are very likely. Such reaction can also produce thermodynamically stable particles like Ba-S-O particles (barite?). Barite on Si-rich substrata is known from rock coatings in the vicinity of fumaroles [2]. Glass and most of the condensate particles will not be preserved for a long time, especially if water or other fluids are present. The degree of modification or alteration of glass can be an indicator of the former presence of fluids or gases. According to paleo-atmospheric conditions, the spectrum of condensates and sublimates might have totally disappeared and only element concentrations can be detected on surfaces or rock coatings applying high resolution EM analysis. As a preliminary experiment, volcanic gas (F0, Vulcano, May 2003) was pumped through a high-T-resistent silicon tube filled with sub-recent diatoms for ca. 1 hour. The skeletons showed sealing of most of the pores and a variety of Pb, Ba, As, Mo(?)-bearing minerals and halite formed on the surfaces.

Mars is known for its long lasting history of volcanic activity. Primitive skeleton-forming organisms could have been preserved by the interaction of volcanic gas, which provided a type of fossilisation. The gas might have changed the structure of the skeletons to a degree unknown or unrecognized on Earth, and the i.e. high Si-bearing skeleton might have served as a catalyst for the formation of more stable minerals indicating the volcanic gas-organic particle interaction. Diatoms can be suspended in the atmosphere and can become substrata for secondary volcanic aerosol particles.

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Graben formation by igneous-tectonic induced terrain deflation in the Shalbatana northern region, Mars

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Observations: Using a MOC NA E0101521 image sub-frame we have analyzed the geomorphology of a graben-like valley in the northwestern Shalbatana region (Fig.1), and recognized three main types of terrains (Fig.1, T1-T3). In T1, there are systems of shallow depressions forming enclosed and interconnected valleys, which intercept craters of different sizes (Fig.1, Red arrows). The smallest crater population is preserved both over the surface of the valleys and over their interceding plains. A valley (Fig.1, VA) intercepts the SE region of crater A (Fig.1, CA) and where interception occurs, there is a sharp-rimmed and locally fracture bounded depression (Fig.1, Srd-1), what is consistent local collapse. On the floor of this depression NE trending ridges (Fig.1, Rd) are exposed. T2 forms the NW flank of the valley floor region (Fig.1, T3). This region has the lowest crater density and there are a large number of modified craters. This terrain is composed of ridge-bounded depressions, which are better developed in the NW part of this region, where there is a sharp-rimmed depression (Fig.1, Srd-2), in which there is some chaotic material suggesting local surface collapse.

Terrain 3 (T3) has an intermediate crater density between T1 and T2. Elongate hill systems with interceding valleys covered by extensive dune mantling. Most of the craters observed in this region have not been modified by ground subsidence.

Interpretation: We propose that there is a transition from T1 to T3 driven by processes, which involved dikes intruding into the permafrost. Fractures acted as escape routes for the volatile phase of the permafrost, what resulted in subsidence of the overlying surface. As the dikes cooled, a mixture of ice and rock sealed the fractures and progressive sublimation took place with loss to the atmosphere being thermodynamically compensated by extraction of the underlying permafrost through the already exiting fracture system over a much longer time scale. Finally, the volatile fraction of the local permafrost was exhausted and subsidence ceased. This hypothesis comprises an alternative, which does not necessarily involve surface extension for the formation of graben-like valleys observed in other regions of the Shalbatana complex [Rodriguez, J.A.P. et al. (2002) *GRL 30*, 1304, 10].

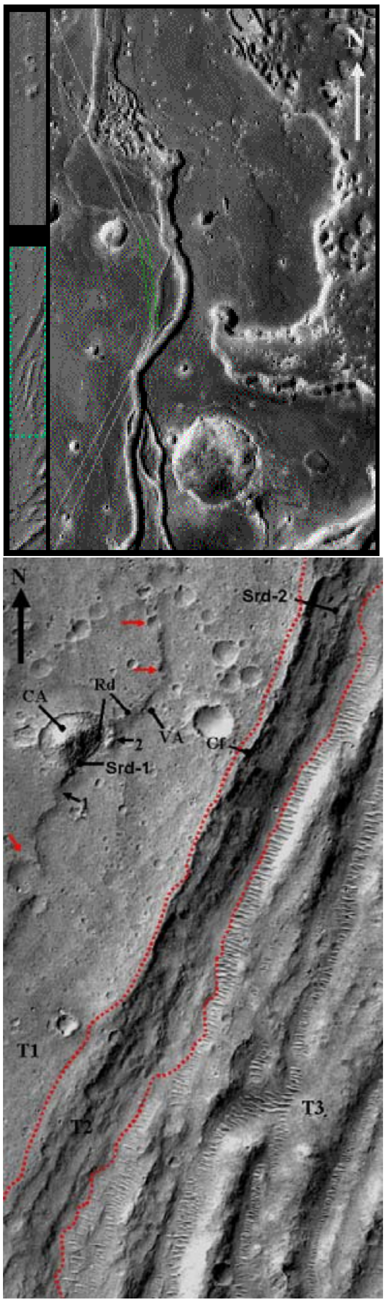

Figure 1. Top: Context for MGS MOC NA E0101521. The crater in the lower left is 35 km in diameter. Bottom: MGS MOC NA E0101521 subframe. Illumination is from the N-NE. The width of the image is 3 km. CA stands for Crater A, Rd for ridge, VA for Valley A, Cf for cliff, Srd for Sharp-rimmed depression, T1-3 for terrains 1 to 3. Red arrows indicate modified craters.

Small cones in Isidis Planitia - evidence for fracture controlled volcanism?

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The European Space Agency's Beagle 2 lander will land on the Martian surface on December 25th 2003. The landing site is within Isidis Planitia, a 1600 km diameter Noachian impact basin with an underlying basement that shows wrinkle ridges [1]. Data from previous orbiting missions to Mars have revealed that Isidis Planitia contains large numbers of sub-kilometre-sized cones, which are found singly, in clusters, or in straight or arcuate chains that often extend many kilometers [2]. They provide clues as to the processes that have contributed to the formation of the surface that the lander will encounter and the nature of volatile-crust interactions within Isidis.

We assess models for the formation of the cones using Mars Orbiter Camera (MOC) and Mars Orbiter Laser Altimeter (MOLA) data from Mars Global Surveyor, and Thermal Emission Imaging System (THEMIS) data from Mars Odyssey. We have carefully analysed the cones and the terrain on which they are found. An important observation is that there are apparently no lava flows associated with any of the cones. For this reason we suggest that they are tuff cones formed by explosive eruption driven by interaction between magma and volatiles (most likely water) in the shallow sub-surface rather than being a result of effusive magmatism. Isidis may contain some of the clearest evidence yet identified on Mars for explosive eruptions.

As well as detailing the morphology of the cones themselves, we have discovered that there appears to be a coincidence between the orientations of many of the cone chains with features that are interpreted as wrinkle ridges formed by compression. This implies a cone-forming environment influenced by fracture-released volatiles or magma.

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Sub-ice volcanism: hydraulics, edifice structures and implications for Mars examples

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Eruptions beneath glaciers on Earth have unique characteristics that enable the resulting deposits and landforms to be used to document the presence, distribution and properties of glaciers over geological time. Many glacier characteristics are uniquely preserved in subglacial volcanic sequences, and the sequences are important repositories of palaeoenvironmental information. On Mars, the presence of polar ice caps and formerly more extensive glaciers makes it permissive that sub-ice volcanism has also played an important part in its history. Moreover, the characteristics of any subglacially erupted volcanoes on Mars can be used to deduce information on past environments otherwise currently unobtainable. Terrestrial examples of sub-ice eruptions are relatively well understood, with thermodynamic and hydraulic models already published. Comparable models do not yet exist for Mars. Moreover, without access to the kind of detailed lithofacies analysis available for terrestrial examples, the internal architecture of putative Mars edifices remains almost completely unknown. Planetary variables, such as low Mars gravity and atmospheric pressures, significantly modulate subaerial eruption dynamics but are less important in subglacial eruptions. Edifice morphology is particularly strongly affected by the simple presence of surface ice, its thermal regime and rheology, which determine the hydraulics associated with the eruptive system. Hydraulics, in turn, determines the sequence and types of lithofacies formed and their architecture. There are significantly different implications for edifices formed in association with both temperate and polar ice that can be used to predict and assess putative examples on Mars. For example, under polar ice conditions, 1) lava-fed deltas are likely to be quite short; 2) subaqueous tuff cones (*tindars*) will be taller, with essentially horizontal beds of fine grained tephra and few sequence discordances compared with their submarine or temperate ice equivalents; and 3) tuyas can exceed 1000 m in thickness (and may be *diagnostic* of eruptions in association with polar ice).

Seismic volume visualisation: a new tool for understanding volcanism.

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Seismic reflection data is routinely collected by the petroleum industry and in many sedimentary basins around the world (e.g. the U.K. Atlantic margin) these datasets contain preserved volcanic successions that were buried shortly after their formation and consequently preserved in pristine condition. However, the traditional analysis of such datasets cannot provide a sufficient level of detail to make a significant impact on the study of volcanism. Recent advances seismic visualisation technology (especially opacity rendering) allows the data to be examined in a new way that is similar to the analysis of satellite images or aerial photographs. Furthermore, with spatial resolutions of 12.5m the technique provides a unique opportunity to expand the frontiers of volcanology using material that is currently available. The new technique relies on the conversion of conventional seismic data into a voxel volume (voxel = 3D pixel). Each voxel contains the information from the original portion of the seismic volume that it occupies together with an additional user-defined variable that controls its opacity. As the seismic response of basaltic lava flows and the associated doleritic intrusions usually yields higher seismic amplitudes compared to the surrounding sediments this technique allows the removal of the surrounding country rock to reveal the true three-dimensional architecture of basaltic magmatic systems. This is achieved by making the higher amplitude voxels (basaltic material) opaque whilst the low amplitude voxels (sediments) are made transparent.

Opacity rendering techniques applied to 3D seismic data from the North Rockall Trough (fig. 1) demonstrates that a range of volcanic features indicative of eruptive style can be recognised. The data reveals a complex terrain containing a range of volcanic features with lava flows originating from discrete volcanic centres up to 4km wide, contemporaneous normal faults, linear fissures a few kilometres long, ring dykes and inflation ridges. Lava flow morphologies indicative of tube fed inflated sheetflows, intracanyon flows and elongate subaerial flows are observed. The intrusive component (doleritic sills) can also be imaged using these techniques. This reveals a branching hierarchy of magma tubes which climb upwards and outwards from the centre of each sill to produce the distinctive 'saucer-shaped' morphology. The results show that magma flow within the area under investigation was complex with magma conduits widely distributed across the region.

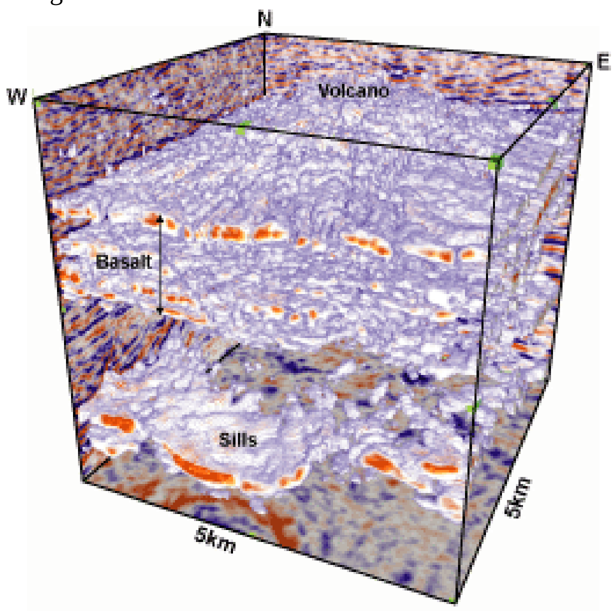

Fig. 1: Opacity rendered image of a basaltic volcano and the underlying doleritic sills.

Structural Evolution of Cerberus Fossae, Mars

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The Cerberus Fossae dike/graben system has been suggested to be the site of recent volcanism on Mars. Through utilisation of MOC, MOLA and THEMIS data, and the techniques of structural geology, we unravel the evolution of Cerberus Fossae to assess the manner in which fracturing, cryosphere derived water and volcanism may have interacted through time. We have measured vertical offsets across the graben walls using individual MOLA traverses, and combined these values to provide profiles, which show how vertical offsets vary along strike. In places, topographic highs and lows can be matched between the footwall and hangingwall of individual graben-bounding faults, suggesting that pre-existing topography has been preserved on the subsiding hangingwalls. We also find deficits in vertical offset at some locations where individual graben segments overlap in an en echelon fashion; other en echelon steps do not show such deficits. The same is true where graben appear to have linked through along-strike propagation. We interpret this to mean that some faults have interacted/linked early in the overall displacement history whilst this occurred later in other examples. We use the implied sequential evolution history to perform a displacement-backstripping exercise for Cerberus Fossae, that reveals how the geometry of the structure changed through time. We use our findings to discuss the temporal pattern of displacement accumulation with respect to cracking of the cryosphere and release of aqueous flood waters on Mars.

Recent volcano-cryosphere-hydrosphere interactions on Mars.

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At least some of the outflow channels on Mars were formed when giant radial dyke intrusions from major volcanic centres fractured the cryosphere and released water floods from pre-existing aquifers [1]. We infer that the water was not produced by local volcanic melting of ice, because dykes cannot transfer heat to a large enough volume of cryosphere to produce the amounts of water implied by the channel geometries. Sills can melt ice in the cryosphere and this may contribute to some floods, but even the largest areas of chaos taken as evidence of this process could not contribute enough water to explain the larger floods.

We examined the source of the Athabasca Valles emanating from the Cerberus Fossae [2] and proximal parts of the Mangala Valles fed by one of the Memnonia Fossae. Morphometry of the Mangala Valles (using a better model of water flow in channels than that employed by earlier workers) leads to smaller fluxes by a factor of ~2 than previously accepted values. Even so, these floods could only be sustained by water release from aquifers on Mars if the sub-surface permeability were very large, $\sim 10^{-6}$ m^2, in line with recent estimates by Hanna & Phillips [3].

Some outflow channels are ancient whereas others (especially the Athabasca Valles) are geologically very young [4]. This implies that dyke intrusions have occurred recently on Mars. We estimated average construction rates of major Martian shield volcanoes from measured total volumes and inferred construction time spans [5]. Construction rates are too small to explain the creation and maintenance of magma chambers with the sizes implied by the observed summit calderas. Periods of rapid magma supply (forming new magma reservoirs) must alternate with periods of negligible supply (to allow old reservoirs to cool enough that new ones are offset from old ones). The analysis implies active periods ~1 Ma long and quiet periods ~100 Ma long. Combined this with the evidence from the outflow channels, this implies that several volcanic centres on Mars are potentially active (though we are unlikely to see activity in our lifetimes).

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