Mercury's surface and composition to be studied by BepiColombo

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Abstract

We describe the contributions that we expect the BepiColombo mission to make towards increased knowledge and understanding of Mercury's surface and composition. BepiColombo will have a larger and more capable suite of instruments relevant for determination of the topographic, physical, chemical and mineralogical properties of the surface than carried by NASA's MESSENGER mission. We anticipate that the insights gained into the planet's geological history and its current space-weathering environment will enable us to understand the relationships between surface composition and the composition of different types of crust. This will enable estimation of the composition of the mantle from which the crust was derived, and

lead to better constraints on models for Mercury's origin and the nature of the material from which it formed.

1 Introduction

The two spacecraft of the BepiColombo mission are scheduled to arrive in orbit about Mercury in 2020 (Fujimoto et al., this issue; Hajakawa et al., this issue). By then the fly-by and orbital phases of NASA's MESSENGER mission (Solomon et al., 2001, 2007) should have advanced our knowledge considerably, but many issues will inevitably remain unresolved. Here we outline measurements to be made by BepiColombo that are intended to enhance our understanding of Mercury's surface and composition, and then discuss the 'Big Questions' that these measurements should help us to answer.

BepiColombo's instruments and their capabilities are described in detail in individual papers (most of them elsewhere in this issue) so we do not assess them individually here. However, for convenience those on the BepiColombo Mercury Planetary Orbiter (MPO), which is the craft most relevant to study of Mercury's surface and composition, are listed in Table 1.

Our recent understanding of Mercury has been well reviewed by Strom (1997), Solomon (2003), Strom and Sprague (2003), Clark (2007) and Head et al. (2007). Additional insights from the first MESSENGER flyby are summarized by Solomon et al. (2008).

Mercury's high uncompressed density indicates a metallic mass-fraction at least twice that of the other terrestrial planets (e.g. Solomon, 2003). A large iron-rich core is postulated, occupying about 42% of the planet's volume and 75% of its radius. Studies of Mercury's libration in longitude have revealed this to be at least partly molten (requiring a light alloying element to lower the melting temperature), and this strengthens the hypothesis that the planet's magnetic field is generated by a core dynamo (Margot et al., 2007). Despite the enormous quantity of iron inferred in its core, optical spectra suggest that Mercury's crust has low (<3 wt%) iron oxide abundance, supplemented by nanophase metallic iron (both meteoritic and resulting from space weathering) amounting no more than about 0.5 wt% (Hapke, 2001; Warell and Blewett, 2004; McClintock et al., 2008). Low iron oxide abundance is also indicated by the regolith's remarkable transparency to microwaves (Mitchell and de Peter, 1994; Jeanloz et al., 1995). Fractionation of iron during partial melting or modest fractional crystallization is slight (Robinson and Taylor, 2001), with the consequence that Mercury's low crustal abundance of iron implies a similar but probably somewhat lower iron abundance in its mantle. For example, Taylor and Scott (2004) note that the abundance of FeO in terrestrial mid-ocean ridge basalts exceeds its abundance in primitive mantle by a factor of 1.3. This low iron abundance in Mercury's bulk silicate fraction could be a consequence of a radial oxidation gradient in the solar nebula, and hence in the local planetesimals that contributed the bulk of Mercury's matter (Robinson and Taylor, 2001), or result from one or more giant impacts that removed Fe-rich crust and upper mantle during the series of collisions by which Mercury was assembled.

Several models have been proposed to explain the large size of Mercury's core relative to the bulk silicate fraction, now represented by its mantle + crust (e.g., Taylor and Scott, 2004). These models fall in to three basic categories:

- selective accretion
- post accretion vaporisation
- crust/mantle loss resulting from a giant impact.

In the first of these models the oxidation gradient during solar nebula condensation, aided by gravitational and drag forces, resulted in an enrichment of metallic iron compared to other terrestrial planets (Weidenschilling, 1978). In the second, intense radiation from the young Sun led to vaporisation and loss of silicates from Mercury's exterior after the planet had formed (Cameron, 1985), or possibly from the differentiated exteriors of planetary embryos before they collided to form Mercury. In the third model, a giant impact stripped Mercury of much of its rocky exterior (Benz et al., 1988, 2007). Some different predicted compositions for Mercury's averaged mantle + crust, resulting from the proposed models, are given in Table 2. If BepiColombo measurements of Mercury's surface can be used to deduce the average composition of Mercury's bulk silicate fraction, this will provide a major test to discriminate between these competing models.

However, it would be unreasonable to expect the abundances of the elements on Mercury's surface to be representative of the planet's bulk silicate fraction, and they certainly cannot correspond to the planet's overall composition. Such may be the case (after due allowance for space weathering) for undifferentiated bodies like most asteroids, but Mercury clearly has a differentiated structure, besides which its surface is heterogeneous in age, morphology and spectral properties (Robinson and Lucey, 1997; Strom, 1997; Sprague et al., 2002, 2007; Warell et al., 2006, Robinson et al., 2008). Determination of Mercury's bulk silicate composition on the basis of what we can measure at the surface can be achieved only after identification and understanding of the nature and history of crust formation and of subsequent surface processes.

Almost irrespective of the mechanism by which Mercury grew, accretional/collisional heating makes it highly likely that the body we now know as Mercury was covered by a magma ocean before any of its present surface was formed. Using concepts fully applicable to Mercury, Taylor (1982, 1989) defined two distinct ways in which planetary crust may form during and after freezing of a magma ocean. Primary crust (for example, the feldspathic lunar highlands) is built by floatation of agglomerations of low-density crystals that grew by fractional crystallization within the cooling magma ocean. Secondary crust (for example, the lunar maria) arrives later in the form of magma produced by subsequent partial melting of the mantle, and is emplaced volcanically upon, or intrusively within, older crust. The mantle from which secondary crust is extracted is likely to be broadly similar in composition to the former magma ocean, but will be deficient in those elements preferentially fractionated into primary crust. This may be a small effect for major elements (e.g., Al, Ca), because the volume of primary crust extracted from the mantle is small in proportion to the total silicate fraction of the planet. However, the effect may be significant for chemically incompatible elements preferentially concentrated below the crust in the last volume of the magma ocean to crystallize, in a manner analogous to the formation of a KREEP-rich mantle layer below the lunar crust (e.g., Shearer et al, 2006).

We note that in the case of differentiated planetary bodies stripped (perhaps more than once) of their crust and uppermost mantle by giant impacts, the process of primary crust formation can begin again in the new magma ocean, and in due course new secondary crust could follow. The volumes and compositions of both types of crust would be different in each generation, and so the compositions that we measure must contain clues to the history of giant impacts and magma oceans. For example, if Mercury's relatively thin mantle is indeed a consequence of an early giant impact event, we might expect KREEP-rich materials to be absent. Moreover, to the extent that Fe and Ti are also preferentially concentrated into later stages of magma ocean crystallization, and thus towards upper mantle layers (see Fig. 4.10 of Shearer et al., 2006), removal of the uppermost mantle by giant impact(s) prior to density-driven mantle overturn (as hypothesised for the Moon by Hess and Parmentier, 1995) might explain the apparently Fe-poor nature of Mercury's mantle.

However, irrespective of previous history, the contrasting modes of origin of primary and secondary crust mean that their composition, and the relationship between their composition and the bulk silicate composition of the planet, will be different. Thus, if we wish to measure crustal composition and use this to deduce the composition of the underlying mantle (or of the bulk silicate fraction of the planet), it is vital to understand what type of crust we are observing, and to distinguish between measurements of primary crust and secondary crust rather than aggregating them together.

If large exposed tracts of primary crust composition have survived on Mercury, they are likely to be in the heavily cratered terrain, and also in intercrater plains if any parts of those are ejecta deposits of redistributed primary crust (Wilhelms, 1976; Strom, 1997). The smooth plains, which have a younger crater age, are long-established candidates for volcanically-emplaced secondary crust (Strom et al., 1975), although it seems likely that their iron content is too low for them to be a familiar sort of basalt. Data from the first MESSENGER fly-by strengthen the view that there are multiple generations of volcanic activity preserved on Mercury (Head et al., 2008; Murchie et al., 2008; Robinson et al., 2008; Strom et al., 2008), including at least some parts of the intercrater plains.

It may turn out that secondary crust emplacement by volcanism has been so widespread that primary crust is no longer exposed in situ except in uplifted crater peaks, inner walls of craters, and tectonic scarps. However, the 'low-reflectance material' identified by Robinson et al. (2008) in ejecta blankets, including that of the Tolstoj basin, may have been excavated from the buried primary crust. Multiple episodes of volcanism in some parts of Mercury (Head et al., 2008; Murchie et al., 2008) offer an opportunity to study Mercury's history of magmagenesis and magma fractionation. It is unlikely that Mercury has any extensive tertiary crust resulting from melting and differentiation of older crust (Taylor, 1989), but if this does occur it will be important to recognise it and interpret its composition separately. The picture may be further complicated if Mercury has impact-melt sheets in which former primary and secondary crust have been intermingled, each in significant proportions. In addition, studies of Mercury's surface and its composition will allow us to document and understand the processes of space weathering and volatile release and/or migration (which will affect the observed surface composition) and the tectonic and impact processes that have shaped the planet.

2 Measurements

We review here various attributes of Mercury's surface that can be measured or determined from BepiColombo data: these are topography/morphology, geological units, regolith physical properties, crater statistics, mineralogical composition of surface materials, elemental abundances in surface materials, space weathering, and polar volatiles.

2.1 Topography and morphology of the crust

Mercury's crust has only a modest range of elevations, generally less than 2 km and rarely exceeding 3 km (e.g. Harmon and Campbell, 1988; Cook and Robinson, 2000). The most significant elevation changes are related to impact craters and basins whose rims can reach elevations of 2 km (e.g. Strom and Sprague, 2003), compressional lobate scarps ranging in height from few hundred meters to 3 km (e.g. Strom et al., 1975; Watters et al., 1998; Cook and Robinson, 2000) and the rugged hilly and lineated terrain at the antipode to the Caloris basin (e.g. Schultz and Gault, 1975; Melosh and McKinnon, 1988; Neukum et al., 2001). Minor morphological features include wrinkle ridges and grabens inside the Caloris basin (e.g. Watters et al., 2005). Volcanic vent structures were reported by Head et al. (2008), and although sinuous rilles have not yet been detected they cannot be ruled out.

BELA will determine the topography of Mercury's crust on global to local scales (Thomas et al., 2007). The initial density of spatial measurements is defined by the along-track shot-to-shot distance of about 260 m and the cross-track distance of about 25 km at the equator. Density will increase considerably as more orbits are completed, which will be particularly beneficial for filling the gaps between the more widely-spaced ground tracks in equatorial regions. The vertical precision of the measurements will be in the order of one meter or even better. These measurements will complement and improve the laser altimetry provided by the MESSENGER Laser Altimeter, MLA (Solomon et al., 2001; Krebs et al., 2005).

On local scales (a few kilometres), consecutive measurements at a spacing of ~260 m along single BELA tracks will constitute a powerful tool for the investigation of specific landforms. Impact craters are particularly well suited for analysis by such profiles, since they usually have axisymmetric topography. Because impact cratering is probably the dominant geological surface process through time on Mercury, the morphology of impact craters can reveal important properties of the target material and/or the effects of velocity on the crater size-frequency distribution. BELA profiles crossing crater centres will be sufficient to characterize key morphometric parameters of crater populations, like the depth-to-diameter relationship or the rim height (e.g., Pike, 1988; Melosh, 1989; André and Watters, 2006).

Laser profiles, in particular in combination with imaging data, can also yield insights into the rheology and emplacement mechanism of lava flows, based on measurements of slope and flow thickness (e.g., Glaze et al., 2003; Hiesinger et al., 2007). Slope will be easy to determine, but ability to determine flow thickness may be compromised by degradation of flow margins.

The stereoscopic channel (STC) of SIMBIO-SYS will provide a 3D global colour coverage of the surface with a spatial resolution of 50 m/pixel at the equator and 110 m/pixel at the poles. The estimated STC precision in elevation is calculated to deteriorate from about 80 m at the equator in the periherm arc, to about 150 m at the pole and to 215 m at the equator in the apoherm arc (see Cremonese et al., 2008; Flamini et al., this issue), as a result of the ellipticity of the orbit and taking into account off-nadir looking sensors. In addition a series of simulations has been performed using Earth analogues (a crater, a lava cone and an endogenous dome complex) of structures expected on Mercury's surface, small enough to be near the detection limit of the STC (Massironi et al., 2008). The results indicate that for data acquisition from periherm, shapes and dimensions are well reconstructed, although minor details such as variations in surface roughness and joints cannot be rendered (BELA is more suited for roughness estimates). As regards crater science, this means that studies of the degree of maturity, depth analyses, slope stability, resurfacing and deformation processes will be very reliable even for small craters (at least down to 2.5 km in diameter) having low depth/diameter ratios (1/15, 1/20). In addition, reliable size measurement and basic classification of volcanic features as small as 1.5 km in diameter and 120 m in elevation could be achieved. At the poles, the accuracy will be sufficient to reconstruct convex landforms and simple crater shapes in 3D, although quantitative morphological analyses based on polar DTMs (digital terrain models) produced by single stereo-pairs should be treated with caution. Fortunately, BepiColombo's polar orbit will result in multiple stereo images of regions near the poles, enabling construction of DTMs with an accuracy comparable to that achieved at periherm. The integration of BELA and STC data will provide even better-constrained DTMs, including by eliminating any steep-slope occlusion phenomena affecting STC acquisitions.

MIXS will make use of morphological information provided by BELA and SIMBIO-SYS to correct the raw measurements for regolith properties and the effects of incidence angle and shadowing.

2.2 Discrimination of geological units and stratigraphy

It is very likely that the MESSENGER and BepiColombo missions will lead to refinement and subdivision of the basic stratigraphic/tectonic units identified on Mariner-10 images (e.g. Spudis and Guest, 1988), by means of clearer and more complete documentation of morphology, context, texture and spectral signature. Analysis and mapping of stratigraphic and tectonic contacts between geological units is the basis for establishing the sequence of events responsible for the current appearance of Mercury's surface. The hyperspectral potential of SIMBIO-SYS VIHI (Flamini et al., this issue) together with the SIMBIO-SYS STC and BELA three-dimensional rendering capabilities will allow the discrimination of different geological units and constrain their mutual stratigraphic relationships across extended regions; consequently a satisfactory knowledge of global stratigraphy will be achieved. The powerful high resolution potential of SIMBIO-SYS HRIC (up to 5 m/pixel; Flamini et al., this issue) will provide additional insights into the characterization of geological units and essential information on the relationships of embayment (onlap) and mutual intersection between different deposits and structural features. In addition, stratigraphic analysis could be performed even for subsurface layers using three-dimensional morphology of craters coupled with spectral information derived by SIMBIO-SYS channels.

The spectrometer channel of MERTIS covers the spectral range from 7-14 µm with a spectral resolution better than 200nm, while the radiometer channel covers the spectral range up to 40 µm (Hiesinger et al., this issue), and will provide complementary spectral discrimination to SIMBIO-SYS (see section 2.5). MERTIS will map the planet globally with a spatial resolution of 500 m and a signal-to-noise ratio of at least 100, and will map 5-10% of the surface with a spatial resolution smaller than 500 m. For a typical dayside observation the signal-to-noise ratio will exceed 200 even for a fine-grained and partly glassy regolith. The flexibility of the instrumental setup will allow adjustment of the spatial and spectral resolutions to optimize the S/N ratio under varying observing conditions. In addition, by use of its radiometer channel, MERTIS will be able to measure thermo-physical properties of the surface such as thermal inertia and internal heat flux, and derive from this further information on surface texture and structure.

MIXS will provide the main source of information on element abundances within the units mapped by the higher resolution imaging systems, and should be able to confirm whether or not the elemental composition of units is consistent with interpretations based on morphologic and spectroscopic information. There are a number of simple tests that can be made using major element abundances to confirm the identification of primary and secondary crust (Fraser et al., this issue). For example, both Fe and Mg should be less abundant in primary crust than secondary crust, but Ca and Al should be more abundant in primary crust. The expected differences are about a factor of two in each case; compare the lunar situation, where Apollo 16 highland soils are characterised by FeO, MgO, CaO and Al_2O_3 concentrations of about 5, 6, 15 and 27 wt%, respectively, whereas the corresponding values for mare basalts are about 16, 10, 10 and 10 wt% (Haskin and Warren, 1991).

MIXS data will also be used to seek geochemical sub-units within major terrain units that lack any more obvious distinguishing features; a lunar analogy would be the Procellarum KREEP terrain whose extent is defined primarily by anomalous Th concentrations (Jolliff et al., 2000). MIXS-T will be able to probe the stratigraphy of the mercurian crust crust to depths of up to several tens of km by determining the major element geochemistry of the central peaks and/or ejecta blankets of impact craters in the diameter range ~50 to 300 km. Such craters will have excavated crustal materials from depths of 5 to 30 km respectively (e.g. Melosh, 1989), and materials from just below these depths will be exposed in rebounded central peaks. By analogy with the Moon (e.g., Jolliff, 2006), variations of the Fe/Mg ratio with depth can be used to discriminate between different models of crustal evolution. These studies will benefit from very high spatial resolution of MIXS-T (~20 km under normal solar conditions, and up to a factor of ten better during solar flares; Fraser et al., this volume).

The roughness of a planetary surface is a function of its geological history. Surface roughness is, therefore, a parameter that can be used to distinguish geological or geomorphological units (e.g., Bondarenko et al., 2003; Cord et al., 2007). BELA will provide roughness information at different scales: on large scales, the roughness is determined by the elevation differences between the individual laser measurements. Roughness can be calculated over specific “baselengths” (i.e. over a specified number of shots along the groundtrack). Kreslavsky and Head (2000) used this technique to show that surface roughness on Mars is correlated with geology, and they found that different geologic units display distinctive roughness characteristics at kilometre-scales. Smaller scale roughness is discussed in the next section.

2.3 Physical properties of the regolith

2.3.1 Optical photometry

The reflectance spectrum of a particulate medium depends not only on its composition, but also on its physical properties and especially particle size. This controls the strength and presence of spectral absorption features, and how band contrast and spectral slope vary with viewing geometry. In practice, these dependences make it difficult to compare spectra acquired under different geometries, because of uncertainty over whether variations are a response to differences in composition, in particle size, or in surface roughness. Photometric measurements therefore have two purposes: first to provide information on the local characteristics of the surface regardless of variations due to observing conditions, and second to characterize these variations so that measurements can be corrected to a common geometry. A third possible application is related to the thermal balance at the local scale, since the incoming solar flux is weighted by the phase function of the medium.

Reflectance spectra from the UV (ultraviolet) to the NIR (near-infrared) can be described by specific radiative transfer models in the geometrical optics approximation, which assumes that the particles are much larger than the wavelength. Two such models are commonly used in planetary science, with numerous variations (Hapke, 1981, 1993; Shkuratov et al., 1999). Both provide an expression of the reflectance at a given wavelength in terms of observing conditions (incidence, emergence, and phase angles) and physical properties. In Hapke's model, the parameters are the single scattering albedo, the asymmetry parameter of the phase function, and surface roughness. In Shkuratov's model they are the optical constants, grain size and porosity. Inversion of these models on the data provides these quantities locally, provided that sufficient measurements at different phase angles are available (ranging from 15° to at least 60°). Study of the opposition effect (for phase angles < 15°) allows derivation of the mean particle size and/or constraints on the size distribution. Furthermore, numerical methods for coherent backscattering and shadowing by particulate media can be applied to constrain the physical properties of Mercury' regolith (e.g., Muinonen et al., 2002; Muinonen, 2004; Parviainen and Muinonen, 2007).

Since these effects are expected to affect mainly the spectral slope in the NIR, such observations are chiefly relevant for the VIHI channel of SIMBIO-SYS. For BepiColombo study of Mercury, low resolution observations will be sufficient to derive the physical properties of the regolith associated with major geological units, although high resolution may be interesting in specific areas such as ejecta blankets or patterned areas of high-albedo known as swirls (Dzurizin, 1977; Starukhina and Shkuratov, 2003). Lunar swirls have very specific photometric behaviour, which gives insights into their origin, and display rapid spatial variations (Kreslavsky and Shkuratov 2003) that may also be evident on Mercury. Spectral coverage is also interesting, most notably to derive the single scattering albedo and roughness estimates at various scales. In more uniform areas the spectrometers will provide photometric information relevant for study of possible regional variations in space weathering effects (Sprague et al 2007).

2.3.2 Laser altimetry

The returned BELA laser signal can be used to measure the local surface roughness and the albedo, including within permanently shadowed polar craters. The shape of the returned laser pulse yields information on the roughness within the spot size of the laser beam on the ground. Such an analysis was performed for MOLA data by Neumann et al. (2003), who showed that the lowlands of Mars are smooth at all scales, while other locations are smooth at long wavelengths but rough at the MOLA footprint scale.

2.3.3 X-ray fluorescence

MIXS will measure the fluorescent intensity of elemental lines emergent from the surface as a function of the viewing geometry. These measurements can be synthesized into a phase curve that can subsequently be compared against semi-empirical models to obtain additional information on the surface roughness of different terrain types. Even though this method will be limited to quite large spatial units, it may help to constrain the most likely parameters for physical properties of the regolith obtained through other investigations. Parviainen and Muinonen (2007) have assessed shadowing effects due to the rough interface between free space and the regolith, and Näränen et al. (in press) have carried out laboratory studies of the regolith effects on X-ray fluorescence.

2.4 Relative and absolute dating

The cratering record is the primary tool for dating planetary surfaces, and also provides important information on the origin of impacting objects whose size-frequency distribution and impact rates could both have varied during the planet’s history. The possible sources of impactors onto Mercury’s surface include the Main asteroid belt, Near-Earth asteroids, comets, and hypothetical asteroids with orbits closer to the Sun than Mercury known as vulcanoids (Strom et al. 2005; Bottke et al. 2005; Cremonese et al. 2008). Large ejecta from any of these can also produce secondary craters.

The size-frequency distributions of craters on the Moon and their calibration against absolute ages derived from Apollo samples allowed cratering chronology models to be determined, and adapted for use on Mercury (e.g. Strom and Neukum, 1988; Neukum et al., 2001a,b). According to these models and Mercury's cratering record based on Mariner 10 data, internal activity of Mercury seemed to have been initiated earlier than that on the Moon, but also to have ended sooner.

However, models of the planetary interior and thermal evolution are not yet in full accord with the conclusion of crater counting studies on Mariner data since the conditions allowing both limited internal activity and radial contraction after 4 Ga, and the persistence of a hydromagnetic dynamo remain unclear (e.g. Hauck et al., 2004). In addition, crater counts based on imaging from the first MESSENGER flyby (Strom et al., 2008) showed that smooth plains exterior to the Caloris basin have a significantly lower crater density than the interior of the basin (demonstrating that they must be younger; presumably volcanic rather than ejecta from the basin-forming event) and that there is at least one smooth plains area (the interior of the peak-ring basin Raditladi) whose crater density is an order of magnitude lower still, suggesting an age of less than 1 billion years.

The crater chronology on the Moon is well established (e.g. Neukum et al. 1975; Hartmann et al. 1981), but has limitations due the possible biases introduced by crater counting, uncertainty in the attribution of some radiometric ages to specific surface units, and the substantial age gap of the lunar samples between 1 and 3 Ga. Other sources of error can reside in the scaling laws necessary to convert the observed crater distribution into an impact flux for the Moon and hence to Mercury itself. In view of these uncertainties, we should not yet expect total agreement may between the dates of internal activity of the planet inferred from crater counting and the duration of such activity called for by thermal modelling. In order to limit some of these problems (at least the crater counting biases and the adaptation of lunar age calibration to Mercury) a novel crater chronology is under evaluation (Marchi et al., 2008, submitted). This approach depends on a model for the formation and evolution of asteroids in the inner Solar System (Bottke et al., 2005) to derive the impact flux through time on the Moon which is, in turn, converted into crater distribution and calibrated for chronology using the lunar radiometric ages. This approach should provide detailed information on the size and the impact velocity distributions impinging on any body in the inner Solar System, allowing the lunar calibration to be exported with greater precision to Mercury.

The impact crater population on Mercury ranges in size up to at least 1550 km, and there is a wide range in their state of preservation (e.g. Pike, 1988). The highly cratered terrains are characterized by fewer craters with diameter smaller than 50 km than their lunar highlands counterpart (Strom and Neukum, 1988; Neukum et al. 2001, Strom et al. 2005). This is generally attributed to the widespread presence of the intercrater plains, but needs to be better constrained.

Important uncertainties in the definition of the chronostratigraphic evolution of Mercury remain due to the lack of knowledge about the largest part of the planetary surface and the low Mariner 10 spatial resolution. The SIMBIO-SYS STC global coverage will provide the opportunity to date the whole surface of Mercury. In particular, unlike MESSENGER that will not provide high resolution images over the whole planetary surface, the SIMBIO-SYS STC spatial resolution (up to 50 m/pixel) will allow identification of craters with diameter larger than about 0.2 km across the entire globe. This will provide accurate estimates of model ages through crater counting of the different terrains, even for very recent units. Locally, age determination could be achieved or refined also using SIMBIO-SYS HRIC images, on small areas with sufficient crater density provided that secondary craters can be recognised and excluded from the count. All these data will also be useful to better constrain impact flux in the inner Solar System through time.

2.5 Mineralogical composition of different units

Due to the difficulties of observing Mercury from ground, relatively little is known about its surface composition, and Mercury spectra are vulnerable to incomplete removal of telluric absorptions. Some early visible to near-infrared (Vis-NIR) spectra of Mercury displayed an absorption near 1μm (McCord and Clark, 1979) that was attributed to the presence of ferrous iron, which is responsible for prominent 1 μm absorption bands in spectra of the lunar maria and some basaltic asteroids, like Vesta. More recent Vis-NIR spectra of Mercury lack evidence for this band (Warell, 2003; Warell and Blewett, 2004; McClintock et al., 2008), while some other spectra, taken of different parts of the planet, exhibit very weak absorptions near 1 μm (Warell et al., 2006), providing the first evidence that Mercury's surface is compositionally heterogeneous in the near infrared spectral range. Overall, the spectra are indicative of an iron-poor mineralogy, so the 1μm absorption has been attributed to Ca-rich clinopyroxene.

Based on early Earth-based telescopic observations and, especially, on the first images of Mercury acquired by Mariner 10 in 1974, similarities between the Moon and Mercury's surface compositions were suggested (Murray et al, 1974). Several studies subsequently used the Moon as an analogue for Mercury (e.g., Blewett et al., 2002 and references therein), despite differences in their geophysical characteristics, and the fact that many aspects of the origin and evolution of the two bodies are still unresolved (e.g., Lucey et al., 1995; Ruzicka et al., 2001; Solomon, 2003). Lunar anorthosites have been suggested as Mercury analogues from their spectral properties (Blewett et al., 1997, 2002). Lunar pure anorthosite is a highland rock type consisting of more than 90% plagioclase feldspar and containing less than 2–3 wt.% FeO. Comparison between the spectral slopes of lunar pure anorthosites with Mercury spectral slopes indicates mercurian spectra to be steeper (redder) (Blewett et al., 1997). The spectral properties of small farside regions of the Moon that are highly mature and very low in FeO (about 3 wt.%) have similarities with Mercury. However Mercury appears lower in FeO than even these very low-iron lunar areas (Blewett et al., 2002). Warell and Blewett (2004) performed Hapke modelling of telescopic spectra of Mercury. Their favoured model was a 3:1 mixture of feldspar and enstatite, with a bulk FeO content of 1.2 wt.%.

Mariner 10 made no direct measurements of Mercury’s surface composition. However, Blewett et al. (2007) used recalibrated Mariner 10 color image data (UV and orange) to examine spectral trends associated with crater features on the inbound hemisphere of Mercury. These recalibrated Mariner 10 mosaics were used to create two spectral parameter images similar to those of Robinson and Lucey (1997): one able to indicate variations in the abundance of spectrally neutral opaque phases, and one controlled by differences in degree of maturity and/or FeO content. They found that Mercury’s surface features exhibit a variety of colour relationships, discriminable by orange reflectance and the UV/orange ratio. These color-reflectance properties can indicate variations in composition (specifically, the abundance of spectrally neutral opaque phases) and the state of maturity of the regolith. Using this method, they concluded that some craters, such as Kuiper and its rays, are bright not only because they are fresh (immature) but also because Kuiper has excavated material with a lower opaque content than the surroundings. Some other craters, like Lermontov and nearby smaller craters, are probably mature, but remain bright because the material exposed on their floors is poor in opaques, suggesting a 3-4 km surface layer with moderate-opaque abundance overlying deeper opaque-poor material. Disk-resolved visible to near infrared telescope images plus colour imaging and spectroscopic data from the first MESSENGER flyby suggest a similar range of heterogeneity elsewhere on Mercury (Warell and Valegård, 2006; McClintock et al, 2008; Robinson et al., 2008). Combined with laboratory studies of terrestrial, lunar and meteoritic materials (Burbine et al., 2002; Cooper et al., 2001; Hinrichs and Lucey, 2002; Salisbury et al., 1997, Sprague et al., 2002), Mercury's spectra further suggest that its surface is dominated by feldspars and low-iron pyroxene. There is little evidence for iron-rich mafic rocks such as basalt, and lower abundances of dark opaque minerals (such as ilmenite and rutile Ti-oxides, and spinels) than the Moon. In particular, calcium-rich feldspars (labradorite, bytownite and anorthite) and pyroxenes (augite, hypersthene, diopside, and enstatite) have been suggested in a number of spectra from different locations on the planet (Sprague and Roush, 1998; Cooper et al., 2001; Sprague et al., 2002).

However, metallic iron may be an important component of Mercury's regolith. Warell (2003) found that the shape of Mercury's spectrum at wavelengths below 550 nm may be critically important in the determination of the abundance of metallic iron, because its high absorbance at these wavelengths (e.g., Hapke, 2001) causes a change in the spectral slope. However, the spectra acquired by Warell and Blewett (2004) indicated a continuous spectral slope extending to 400 nm.

The determination of surface mineralogy and the origin of geologically significant morphologic features are among the primary objectives of SIMBIO-SYS. The combination of the SIMBIO-SYS STereoCamera (STC) with its broad spectral bands in the 400-900 nm range and medium spatial resolution (up to 50 m), and the Visible-near Infrared Hyperspectral Imager (VIHI) with its 256-channel hyperspectral (about 6 nm) resolution in the 400-2000 nm range and spatial resolution up to 100 m (Flamini et al., this issue), will be powerful tools for discriminating, identifying and mapping variations in the surface reflectance spectrum. They will provide higher spatial resolution and broader spectral coverage than MESSENGER, which will collect no imaging or spectroscopic data at wavelengths longer than 1450 nm (Boynton et al., 2007; Solomon et al, 2007).

The VIHI spectral range includes mostly electronic transitions related to Fe in silicate lattices. It is particularly useful for identifying and characterizing pyroxenes from their 1 and 2 μm crystal field transitions, the details of which depend on the Fe/Mg ratio. On the Moon, feldspars are clearly detected in pyroxene-free areas, but less easily when they are mixed, and Fe-bearing olivine is also readily identified (e.g., in central peaks of craters). Furthermore, many salts have specific vibration signatures in this range, and sulfides should also be detected from absorptions in the visible part of the spectrum. The geomorphological information provided by STC will allow the discrimination of different units within the larger footprint of VIHI, helping the interpretation of the hyperspectral spectrum of VIHI mixed pixels.

The 7-14 μm spectral coverage of MERTIS offers unique diagnostic capabilities for the surface composition of Mercury, in a spectral region not covered by

MESSENGER (Helbert et al., 2007). In particular, feldspars can be readily spectrally identified and characterized, by means of several diagnostic spectral features in the 7-14 µm range: the Christiansen frequency, Reststrahlen bands, and the transparency feature. In the thermal infrared range at wavelengths longer than 7 µm, spectral signatures in silicates result from characteristic fundamental Si-O vibrations. Therefore FeO- and TiO_2-free silicates (e.g., feldspars, Fe-free pyroxenes and Fe-free olivines), which are almost undetectable in the visible-NIR region, can be identified. MERTIS will not merely be capable of detecting feldspars, its spectral resolution will allow identification of the member within the series. For example, in the plagioclase series ranging from the sodium-rich end-member albite ($NaAlSi_3O_8$) to the calcium-rich end-member anorthite ($CaAl_2Si_2O_8$), as the paired substitution of Ca^{2+} and Al^{3+} for Na^+ and Si^{4+} progresses, structural changes occur that affect the frequencies of Si–O vibrations, as well as the related Christiansen frequencies. The spectral changes include a progressive shift of the Christiansen maximum and Reststrahlen bands to shorter wavenumbers (longer wavelengths), which will be measurable by MERTIS. By determining abundances of all elements likely to be present in excess of about 0.1% (Fraser et al., this issue), MIXS will act as a test of the credibility of the mineralogy suggested by SIMBIO-SYS and MERTIS, and will enable calculation of the normative mineralogy of different units (of particular relevance to igneous assemblages at equilibrium). MIXS will measure the abundance of the main anion species (O and S), and so provide a test of whether the surface materials are fully oxidised. Furthermore, if MIXS shows Fe to be more abundant than seems consistent with the SIMBIO-SYS and MERTIS mineralogy, this would provide a measure of the amount of nanophase metallic iron at the surface.

2.6 Elemental abundances

Mapping the abundances of the rock-forming elements on Mercury's surface is the main science goal of MIXS (Fraser et al., this issue), which will detect many more elements and operate at higher spatial resolution than MESSENGER's X-ray Spectrometer (Boynton et al., 2007). The achievable spatial resolution depends on the abundance of each element, the strength and distinctiveness of its fluorescent lines, and the solar state (flares increase the stimulus for fluorescence by orders of magnitude). Averaged globally, the abundances of O, Na, Mg, Al, Si, P, K, Ca, Ti, Fe and Ni will be measured to high statistical precision even during solar quiet. With the aid of maps based on SIMBIO-SYS and MERTIS data, it should be possible to subdivide the global dataset of X-ray data into primary crust and secondary crust, with little loss in precision (except for primary crust if exposures are small and rare). Therefore MIXS will be used to determine average abundances of all those elements in each of the two main crustal types. Sprague et al. (1995) argue that sulfur might be widespread in Mercury's regolith in the form of sulphide minerals, and if S is more abundant than about 0.1% MIXS should be capable of revealing it during solar flares. Solar flares may also enable detection of Cr, whose abundance in lavas may exceed 1% or be an order of magnitude less according to different models for mantle composition (Taylor and Scott, 2004).

Higher resolution mapping of elemental abundance should be achieved for the more common elements at all times, and for others during solar flares. For example, under typical solar conditions O, Na, Mg, Al, Si and Fe will be mapped with spatial resolution of tens of km with MIXS-T and 100s of km with MIXS-C. Measurements at the highest spatial resolution, of the order of a few km, will be achieved by MIXS-T during solar flares of M class or stronger for O, Na, Mg, Si, P, K, Ca, Ti and Fe.

These events, expected less than 0.6% of the time (Fraser et al., this issue), will yield serendipitous high resolution data takes lasting about 30 minutes (about a quarter of an orbit), and are expected to be especially useful where they cross the uplifted central peaks of large craters and other units of limited spatial extent such as fresh ejecta blankets, crater walls or fault scarps that may expose variations in crustal composition with depth. Any igneous material with enhanced abundances of Si and alkalis (Na, K) would suggest fractionation during storage in magma chambers, whereas abundant Ti would indicate the minerals ilmenite or ulvöspinel that on the Moon occur only in basalts.

MERTIS would be capable of detecting elemental sulfur, thanks to distinctive spectral features near 12 μm, but this will not work inside the polar cold traps (section 2.8), which are too cold.

The gamma-ray spectrometer of MGNS (Mitrofanov et al., this issue) will detect gamma rays from natural radioactivity (U, Th, K) and stimulated by solar gamma rays (C, Na, Fe, Al, Si) with a surface resolution of about 400 km below the pericentre of the MPO orbit. U, Th and K are chemically incompatible elements, which would have become concentrated near the top of a primordial magma ocean (along with the KREEP elements). As noted above, a deficiency of these elements on Mercury would be consistent with the early removal of the uppermost mantle by a giant impact event.

In situ measurements of the exospheric composition by SERENA will offer an independent check on the element abundances measured by remote sensing techniques, since matter in the exosphere is directly released from the surface (Wurz and Lammer, 2003; Milillo et al., 2005). There are four release processes capable of delivering surface material to the exosphere, which have been discussed at length in the literature (e.g. Wurz and Lammer, 2003; Killen et al., 2007). These processes are thermal desorption, photon-stimulated desorption, sputtering by energetic ion impact, and meteoritic impact vaporisation. The latter two are stoichiometric processes, such that the release of elements into the exosphere (including refractory elements) is proportional to their abundance at the surface.

The release process by sputtering into the lunar exosphere has been studied in detail for typical lunar mineralogical compositions (Wurz et al., 2007). Sputtering releases particles from the topmost atomic layers of the surface. This is where space weathering will be effective, and so must be taken into account when interpreting the data. Unfortunately, exospheric measurements in orbit cannot be closely related to a location on the surface, the likely origin being within a circle of a size equivalent to the spacecraft altitude (Wurz and Lammer, 2003). However, Mercury has a magnetic field that is responsible for a small magnetosphere around the planet. The solar wind can penetrate the magnetosphere and impinge only upon limited areas of the surface (e.g. Massetti et al., 2003). The ELENA sensor of SERENA will detect the sputtered particles with angular resolution of 2° at best, allowing mapping of their origin. Plasma measurements will be performed with the MIPA and PICAM sensors of SERENA, and the places where ion precipitation onto the surface occurs can be inferred from these measurements, in conjunction with the magnetic field measurements by MAG. Moreover, knowing the precipitating ion flux, the sputtered particle release flux plus its source region, and the composition of the exosphere above that region, we will be able to infer the expected exospheric density for a given surface concentration and impacting plasma. Thus, it will be possible to deduce the surface concentration of refractories such as Si, Mg, Ca that are released mainly by ion sputtering from SERENA measurements.

It is also likely that the SERENA-STROFIO instrument will be able to detect concentrations of refractory elements Mg, Al and Si and possibly also Ca and S and molecules released by meteoritic impact vaporisation. Mangano et al. (2007) point out that on average two 1 m impactors may be expected to strike Mercury per year, with a detection probability of >50%, whereas 10 cm impactors strike so often that the likelihood of detecting an event is almost 100% after only one month.

The in situ measurements by SERENA will be even more valuable if the origin of detected material can be identified. For sputtering, the flux of precipitating ions will be measured by SERENA-MIPA, and from that the location of sputtering on the surface could be deduced. For a meteoritic impact the impact location might be observed optically, or can be inferred from the plume when flying through it. A comparison with MIXS composition maps will be fruitful to validate the observations and to estimate the impact location.

During the Mercury flyby of MESSENGER on 14 January 2008 the plasma ion spectrometer, FIPS, detected pickup ions (Zurbuchen et al., 2008). Although the mass resolution of FIPS allows only for the identification of mass groups (Na^+/Mg^+, S^+/O_2^+, K^+/Ca^+, and others) the origin of these ions in the refractory material of the surface is clear. SERENA-PICAM has sufficient mass resolution to resolve all these ions, and thus will contribute to the compositional analysis of the surface. These pickup ions originate mostly from neutral atoms in the exosphere, which were ionised by the solar UV radiation. Since the ionisation process has a low yield, one can infer that the neutral atom densities are orders of magnitude larger and thus direct detection by SERENA-STROFIO will be possible.

2.7 Soil maturity and alteration (the extent, rate and nature of 'space weathering')

"Space weathering" is a term used for a number of processes that act on any airless body exposed to the harsh environment of space (Hapke 2001, Sprague et al., 2007, Langevin and Arnold 1977; Langevin 1997; Cintala 1992; Noble and Pieters 2003, Noble et al., 2007), and must strongly affect the chemistry and observed properties of the mercurian surface. Thus, no interpretation of the composition of Mercury's crust can be made without thoroughly accounting for space weathering, including maturation and exogenic deposition on its surface. On the Moon (Lucey et al., 2006), the products of these weathering processes include complex agglutinates as well as surface-correlated products on individual soil grains (implanted rare gases, solar flare tracks, and a variety of accreted components).

The visible to NIR spectral properties of the regolith of an atmosphereless body like Mercury are governed by three major components (Hapke et al., 1975; Rava and Hapke, 1987; Hapke, 2001): ferrous iron as FeO in mafic minerals and glasses, nanophase metallic iron (npFe^0) particles formed by vapour deposition reduction, and spectrally neutral Ti-rich opaque phases in minerals and glasses. Increases in abundance of these components have different effects on the spectra: ferrous iron increases the depth of the near-infrared Fe^{2+} crystal field absorption band near 1μm, npFe^0 particles decrease the reflectance and increase the spectral slope ("reddening"), and opaque phases have the effect of decreasing both the reflectance and the spectral slope. Images from the first MESSENGER fly-by show well-defined ray craters corresponding to the latest impacts on the surface of Mercury being distinctly "bluer" and brighter than older surfaces, supporting the influence of maturity in the optical properties of Mercury's surface.

Very small abundances of metallic iron as npFe^0 have drastic effects on visible to NIR spectral shape and so must be understood and calibrated out of observed spectra in order to derive the composition of the unweathered material. The size distribution of metallic Fe particles in a soil strongly controls the effects on the visible to NIR spectrum: the larger npFe^0 particles (greater than approximately 10 nm) darken the soil (Keller and McKay, 1993; Britt and Pieters, 1994), whereas smaller particles (below 5 nm) are responsible for more complex continuum-altering effects including a general reddening (Noble and Pieters, 2003). Soil maturation through sputtering to produce npFe^0 particles is expected to proceed on Mercury faster than the lunar rate because of the 5.5 times greater flux and higher mean velocity of impactors at Mercury (Cintala, 1992). On the other hand, the ability of solar-wind protons to reduce FeO in impact melts will be less on Mercury owing to its magnetic field. The rate and style of space weathering on Mercury is expected to be further influenced by 'Ostwald ripening', whereby high daytime temperatures will permit diffusion within glass to allow the average size of npFe^0 particles to coarsen. This effect ought to be greater towards the equator, so equatorial regions are predicted to be darker but less red than polar regions of similar age (Noble and Pieters, 2003).

It should be possible to observe the effects of space weathering in visible to NIR spectra of the type expected to be returned by VIHI, the Visible Infrared Hyperspectral Imager of SIMBIO-SYS. Understanding these weathering processes and their consequences is essential for evaluating the spectral data returned from VIHI in order to determine the abundance of iron and the mineralogy of Mercury's surface. The optical scattering parameters derived locally by SIMBIO-SYS will allow retrieval of global albedo maps at various wavelengths. Spectral mixture modelling will provide an estimate of the fraction of dark, glassy particles at the surface. Knowledge of grain size and glass fraction will allow quantification of maturation effects. Inversion of spectral models should allow simultaneous retrieval of a maturation parameter and the FeO content of surface material (Le Mouélic et al., 2002; Lucey, 2006).

If MIXS were to show Fe to be more abundant than seemed consistent with the mineralogy inferred from SIMBIO-SYS and MERTIS investigations, the difference would provide a measure of the amount of nanophase metallic iron at the surface. Spatially resolved element abundance maps from MIXS will be useful to compare older surfaces from which Na has been lost by sputtering processes with fresh ejecta blankets, where we might expect to find ‘excess’ Na. Note that the SERENA-STROFIO measurements in the exosphere (via sputtering and meteorite impact vaporisation) will be almost independent of the grain size and vitrification of the particles, but merely reflect the atomic composition of the grains undergoing sputtering.

BepiColombo will offer for the first time the opportunity to evaluate the regolith efficiency to eject material when impacted by ions from space, thus providing crucial information about the effects of space weathering and about surface evolution. This will be achieved thanks to specific joint measurements that will permit correlation of the neutral particles observed at thermal energy by the mass spectrometer SERENA-STROFIO and the generation region on the surface mapped through higher energy neutral detection by SERENA-ELENA, together with simultaneous observations of plasma precipitation by ion sensors SERENA-MIPA and -PICAM and to the magnetic field measurements by MERMAG. The surface composition mapped by MIXS, the surface mineralogy mapped by MERTIS and the surface cratering mapped by SIMBIO-SYS will allow the released exospheric atoms to be related to the surface properties.

2.8 Characterising polar volatiles

Permanently-shadowed regions of Mercury's polar craters are anomalous radar reflectors, consistent with either ice or elemental sulfur (Harmon et al., 1994; Sprague et al., 1995), held as a cold-trapped volatile within the shallow regolith. The neutron spectrometer of MGNS (Mitrofanov et al., this issue) will place constraints on the amount of hydrogen and, by inference, water-ice in polar regions (with an accuracy of 0.1 g cm^{-2} and a surface resolution of about 400 km) by characterizing the epithermal neutron flux, as achieved on the Moon by Lunar Prospector (Feldman et al., 1998). If sulfur is present, it may prove detectable by MIXS thanks to X-ray fluorescence induced by electrons reaching the surface along magnetic field lines. It may also prove possible to image any polar deposits optically by light reflected from the opposite walls and central peaks.

The topography of landforms in an ice-rich substrate material can become subdued due to relaxation by ice-enhanced creep of the regolith ("terrain softening"; e.g., Squyres and Carr, 1986). Possible (subsurface) ice deposits at Mercury`s poles might produce a similar effect (e.g., Barlow et al., 1999), which could be identified by precise topographic measurements by BELA of, for example, the depth-to-diameter relationships of permanently shadowed craters. Furthermore, BELA will also be able to detect the relatively high albedo of any ice-rich surfaces within shadowed polar craters.

3 Data products

3.1 Photomosaic maps

The US Geological Survey published 1: 5 million scale shaded-relief maps and photomosaics based on Mariner-10 images (Davies et al., 1978), dividing Mercury into fifteen quadrangles recognised by the International Astronomical Union (although less than half the planet was imaged). This product type is important for regional studies particularly for the reconstruction the tectonic settings and geological/compositional context. An important outcome of the BepiColombo mission will be the production of photomosaics of each quadrangle based on SIMBIO-SYS STC images (up to 50 m/pixel in the original data), providing details of the surface at higher resolution than MESSENGER images (which will range in resolution from ~100 to 500 m/pixel for most of the planet's surface). Larger scale photomosaic maps (1:1 million or better) will be produced for limited areas containing interesting morphological and geological features to be selected during the mission activities.

3.2 Topographic maps and digital terrain models

The combination of altimetric and topographic information provided by BELA and SIMBIO-SYS STC will be used to derive global topographic maps and a DTM for the whole planet and for each individual quadrangle. Three-dimensional reconstruction of local topography overlain by images or compositional maps will be used for geological interpretation and public outreach.

3.3 Compositional maps and a Mercury geographic information system

BepiColombo will achieve a wide variety of mineralogical and elemental abundance measurements. Mineralogy will be revealed chiefly by UV-IR reflectance spectroscopy (SYMBIO-SYS) and thermal infrared emission spectroscopy (MERTIS) whereas elemental abundances at spatial resolution adequate for mapping will be revealed chiefly by X-ray fluorescence spectroscopy (MIXS). The resulting dataset will be complex because of its many derivation routes and because its spatial resolution and quality will vary with location and with the time of acquisition. However, with the use of a common spatial reference system and suitable data fusion techniques, it will be possible to set up a geographic information system (GIS) that could be interrogated by the user to find information such as absolute element abundances, element abundance ratios, and mineral abundances for any location on Mercury's surface, together with estimates of the error (uncertainty) in each value. In addition, the Mercury GIS will allow such data to be overlayed on other digital maps or a digital photomosaic base, and could also include crater statistics and surface physical properties such as slope, surface roughness and regolith grain-size. This will be a powerful tool for many studies, such as geological mapping and investigation of soil maturity across the globe.

3.4 Geological maps

Geological maps will provide a visual synthesis of knowledge of Mercury's geology as revealed by the BepiColombo mission. A geological map is a derived product, relying on assimilation and interpretation of multiple datasets. Because it portrays terrain units in a stratigraphic framework, a geological map enables the three-dimensional spatial relationships and the local and regional sequence of events to be made clear (Wilhelms, 1990).

Mariner-10 imagery enabled the production of geological maps of all or parts of nine quadrangles (out of 15) at a scale of 1:5 million, recently converted by USGS into a digital format (http://webgis.wr.usgs.gov/pigwad/down/mercury_geology.htm). The comprehensive coverage by BepiColombo will be sufficient not only to complete this global mapping, with reinterpretation as necessary, but also to produce worthwhile geological maps at 1:1 million scale globally, and at larger scales in regions of special interest. The exact placement of geological boundaries will, in most cases, be done on the basis of the highest resolution SIMBIO-SYS images (stereo images from STC at 50 to 110 m/pixel for the whole globe, and 5 m/pixel images of 20% of the globe from HRIC), but data from several other experiments will feed in to the identification and definition of the extent of each unit.

Regional coverage provided by photomosaics of STC images will show configuration of bedrock, the extent of geological structures, and broad stratigraphic correlations and age assessment from cratering records. The high resolution images from HRIC will show most clearly the details of regolith surface, stratigraphic contacts and onlapping/embayment relationships between bedrock units, and cross-cutting relationships among structures. The third dimension provided by digital elevation models and topographic maps from BELA and SIMBIO-SYS STC data will be fundamental for evaluating thickness of geological units, to relate them to their morphological characteristics and to infer the propagation of geological contacts and tectonic features below the surface (i.e., geological sections and true volumetric three dimensional rendering). The compositional information described in the previous section will help to define geological units on the basis of their lithological characteristics. This last requirement, fundamental for geological unit definition on the Earth, has rarely been applied in the geological cartography of planetary surfaces, which is usually limited to surface morphology, texture, albedo, stratigraphic relationships and indirect age determinations.

4 Big questions

We conclude by considering some of the 'big questions' that BepiColombo's documenttion of Mercury's surface and its composition may be particularly useful in answering.

4.1 What is the tectonic history of Mercury's lithosphere?

Given the small size of Mercury compared to the other terrestrial planets of the Solar System, a prolonged tectonic history is not expected. However, for the same reason, Mercury's surface, like the lunar one, preserves traces of early tectonic processes. These include: tidal despinning and consequent bulge relaxation manifested by the global grid network affecting the ancient cratered regions (Burns, 1976; Melosh, 1977; Melosh and Dzurisin 1978; Melosh and McKinnon, 1988); global contraction due to planetary cooling manifested by widespread compressional lobate scarps (Murray et al. 1974; Strom et al. 1975; Dzurisin, 1978; Watters et al., 1998; Solomon et al, 2008); dynamic loading by giant impacts during heavy bombardment epoch well testified by the basin structures and the hilly and lineated terrains at Caloris antipodes (Schultz and Gault, 1975; McKinnon, 1981; Melosh and McKinnon, 1988, Murchie et al. 2008). The evolution of these phenomena, their mutual relationships and their relations with respect to the progressively thickening of the crust and lithosphere await elaboration based on orbital survey of the kind anticipated from BepiColombo.

The global lineament pattern on Mercury does not fit the predicted models for tidal despinning (Thomas et al., 1988, Thomas 1997). This may be partly accounted for by the incomplete Mariner-10 coverage of Mercury's surface obtained under a single set of illumination conditions, varying across the globe. The three dinmensional surface mapping obtained by SIMBIO-SYS STC and BELA images should lead to more reliable global lineament mapping, almost free of directional bias. In addition, thanks to their resolution, SIMBIO-SYS HRIC images should provide important insights into kinematics related to structural features. Therefore, despinning models will be better constrained and other mechanisms that changed the planet's shape during the early history of its surface may be recognized.

Interpretation of lobate scarps (e.g., Thomas et al., 1988; Thomas, 1997; Watters et al., 2004) is presently hampered by incomplete coverage and paucity of stereo imaging (Cook and Robinson, 2000). DTMs derived from SIMBIO-SYS and BELA will fill this gap and will consistently improve upon present estimates of crustal shortening and decrease of planetary radius (Strom et al., 1975; Watters et al., 1998). In addition cross-sections through lobate scarps derived from DTMs will be used as input to faulting models, resulting in better estimates of fault displacement, paleoseismicity, and the thickness of the elastic lithosphere at the time of faulting (e.g. Watters et al. 2000, 2002; Nimmo and Watters, 2004; Grott et al., 2007). Accurate assessment of the strain across contractional features will offer an important constraint on the amount of global cooling, inner core solidification and hence on the models of the planetary interior and its thermal evolution (Hauck et al., 2004; Solomon et al. 2008).

Long-wavelength lithospheric flexure is another process that can accommodate strain induced by planetary contraction, and therefore it will be investigated using the gravity data resulting from the radio tracking of BepiColombo's Mercury Planetary

Orbiter on the one hand, and the DTM from the BELA and SIMBIO-SYS STC on the other. Furthermore, the same data can give important clues to assess whether there is any correlation between topography and gravity anomalies, and at which wavelengths, or to what extent the topography is supported by the mechanical strength of the lithosphere or, finally, if a mechanism of isostatic compensation needs to be invoked for the larger topographic features.

Recent analysis of the Moon has demonstrated that the detection, geomorphological characterization and depth estimates of multi-ring basins can give important information on the rheology of the ancient lithosphere and mantle (e.g. Mohit and Phillips, 2006). Two multi-ring basins, Caloris and Tolstoj, were particularly apparent on Mariner-10 images. The most interesting characteristics of the Caloris basin are the lack of a well developed ring outside the main crater rim and the presence of extensional grabens superimposed on compressional ridges deforming the post-impact lava plains inside the basin. The lack of a well developed external ring could be due to a thick (>100 km) lithosphere preventing penetration (Melosh and McKinnon, 1988), but additional explanations include later viscous relaxation of topography or smooth plains emplacement over subsiding ring-bounded blocks of the lithosphere (McKinnon, 1981).

The extensional troughs cutting convex shaped ridges inside the basin have been explained through different models (Murchie et al., 2008). The main ones are: subsidence-related compression during smooth plains extrusion outside Caloris followed by isostatic uplift and pellicular extension of the as yet incompletely compensated basin (Dzurisin, 1978; Melosh and Dzurisin, 1978); compression related to subsidence for interior plains load, followed by outer smooth plains emplacement and consequent basin centre uplift and extension as result of the annular load

(McKinnon, 1981); uplift and extension due to lateral flow of the lower part of relatively thick lithosphere toward the basin centre (Fleitout and Thomas, 1982; Thomas et al. 1988 Watters et al., 2005).

A detailed structural analysis, aided by perspective views (BELA and SIMBIO-SYS STC), high resolution (SIMBIO-SYS HRIC) and/or large area coverage (BELA and SIMBIO-SYS STC), will bring important insights on large basin evolution, the focusing of seismic waves after huge impacts, post-impact plains emplacement, and deformation structures inside basins and in the surrounding areas.

4.2 What is the composition of Mercury's crust and how did it evolve?

The surface compositions determined by BepiColombo will be measured across a depth sampling range varying from tens of µm in the case of MIXS to 0.5 m for MGNS. The optical and infrared spectrometers will gather data over a depth range of the order of 1 mm. Almost the entire visible surface will be agglutinate-rich regolith rather than bedrock (Cintala, 1992; Harmon, 1997), which may be vertically homogenised across the depth range of the measurements by impact gardening except in the cases of the most volatile elements and extremely fresh ejecta. In the case of the Moon, homogenisation by impact gardening is effective on vertical scale of 1 m and a horizontal scale of about a kilometre (Mustard, 1997). The rate of gardening on Mercury should be higher because of higher meteorite flux, but lateral transport is expected to be less because of Mercury's higher gravity (Langevin, 1997). Apart from its meteoritic content, which may be as much as 5-20% (Noble and Pieters, 2003), regolith on Mercury is therefore expected to be representative of the underlying bedrock. By making allowance for space weathering (which in any case is unlikely to affect significantly the abundances of elements such as Al, Si and Mg), the composition of the upper crust can be determined in terms of both elemental abundances (primarily MIXS and MGNS) and mineralogy (primarily SIMBIO-SYS and MERTIS). However, it is possible that, as noted by Noble and Pieters (2003), mature soils will be so dominated by glassy agglutinates with so little surviving crystalline material that original crustal mineralogy will be revealed only in freshly-exposed material.

Compositional variability of the shallowest layers of the crust may be revealed by study of large crater walls. Opportunities to study deeper layers may be provided by central peaks of craters (which are uplifted; Tompkins and Pieters, 1999) and floors of any major basins analogous to the Moon's South Pole-Aitken basin that have avoided later infill. Robinson et al. (2008) argue that 'low-reflectance material' identified in MESSENGER images of some proximal ejecta reveals an opaque-enriched crustal layer, which clearly warrants further scrutiny. Finally if lobate scarps are faults that actually cut the surface they may reveal material exhumed from depths of around 1 km (Watters et al., 2000). This may prove to be mineralogically distinct and resolvable by SIMBIO-SYS VIHI, but good exposures are likely to be rare and the width of outcrop will be too narrow to be resolved by the element abundance experiments MIXS and MGNS.

In combination with photogeologic interpretation and crater counting on high resolution images (SIMBIO-SYS) and digital elevation models (SIMBIO-SYS and BELA) we expect to be able to use this information to identify, distinguish and interpret the nature of each major terrain unit within Mercury's crust. Apart from answering the fundamental question of the presence and relative abundances of primary crust and secondary crust, we will have a stratigraphic framework derived from cross-cutting and superposition relationships and crater counting to enable crust-forming events to be placed into context.

We note that if any of the hitherto elusive but statistically possible meteorites from Mercury come to light (Love and Keil, 1995), then a crucial test of their provenance will be compatibility with the mineralogy and element abundances deduced for units in Mercury's crust on the basis of BepiColombo data (Nittler et al., 2004). Any strong meteorite candidate for a sample of Mercury's crust thus revealed would open the way for fuller understanding of Mercury based on its petrography, trace elements and isotopes.

4.3 What is the composition of Mercury's mantle?

Determination of the composition of Mercury's mantle, and hence the composition of its bulk silicate fraction, is an important goal that can be achieved indirectly via an understanding of the nature and composition of the planet's crust. Although we will lack seismic, petrological, trace element and isotopic data such as are available for the Moon (Mueller et al., 1988; Warren, 2004) the BepiColombo measurements described above will place our understanding of Mercury's mantle on a considerably firmer foundation than previously, especially when coupled with BepiColombo's geophysical study of the planetary interior (Spohn et al., this issue). For example, the limited fractionation of Fe during partial melting of mantle material, means that the Fe abundance in secondary crust can be used to define a conservative upper limit to the mantle Fe abundance (Robinson and Taylor, 2001). Using the measured crustal composition as a basis for modelling back to the mantle composition will be more complex than this for most elements. However, provided primary and secondary crust can be correctly identified and distinguished, their contrasting modes of origin may provide a way to avoid at least some of the ambiguities.

4.4 Origin and evolution of Mercury

Taylor and Scott (2004) proposed various ways that knowledge of Mercury's crustal composition could be used to distinguish between the competing models for Mercury's origin. Among these are: low Si but high Mg would support Cameron's (1985) evaporative silicate loss model; lavas with Ca <9% and Fe <0.3% would fit with the enstatite chondrite model for Mercury (Wasson, 1988); Mg of about 10% and Cr 1% in lava would be consistent with Goettel's (1988) refractory-volatile mixture model, whereas other models would predict higher Mg, but Cr of only 0.1%. We also note that P and Ti have similar partitioning behaviour during partial melting, and so Ti/P in lavas should be similar to the mantle Ti/P ratio. This would be about 1 if the mantle retains a chondritic Ti/P ratio, but if (as is likely, but unproven) core formation preceded volcanism, prior scavenging of P into the core would boost the Ti/P ratio to about 10 in secondary crust. Finally if Mercury lost its original crust in a giant impact event, then, as pointed out by Benz et al. (2007), its present crust should be depleted in large ion lithophile elements, and so be relatively poor in K and Ca. As previously noted, the remaining mantle is likely to be depleted in chemically incompatible elements (KREEP), and be relatively iron-poor (as seems to be the case). These effects would be more extreme if the Mercury predecessor body/bodies experienced more than one such episode, and observations by BepiColombo will help to better constrain such giant impact models.

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