Lunar Resources

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1. INTRODUCTION

It has long been recognised (e.g., Ehricke 1985; Spudis 1996, 2016; Duke et al. 2006; Benaroya 2010; Kornuta et al. 2019) that the Moon has the potential to play a pivotal role in the development of a future space-faring civilisation. Indeed, as noted by Duke et al. (2006) in their chapter on the "Development of the Moon" in the first edition of this book (Jolliff et al. 2006a; hereinafter NVM I), the Moon can be viewed as a natural supply station in Earth orbit bearing raw materials that will assist in humanity's continued exploration and development both of the Moon itself and, eventually, the wider Solar System.

The following range of applications for lunar materials has been identified to date:

- Use of lunar materials to facilitate continued exploration of the Moon itself (an application usually referred to as *In Situ* Resource Utilization, or ISRU).

- Use of lunar resources to facilitate scientific and economic activity in the vicinity of both Earth and Moon (so-called cis-lunar space, including operations in Earth orbit).

- Use of lunar resources to support future space exploration activities elsewhere in the Solar System, for example human missions to Mars or the outer planets.

- Importation of lunar resources to the Earth's surface where they could contribute directly to the world economy.

These four possible applications of lunar resources are not mutually exclusive, although they do represent an approximate hierarchy of increasing scale of operations and, therefore, a plausible temporal order of implementation.

Previous reviews of lunar resources relevant to one or more of these applications have been given by, among others, Lewis et al. (1993), Spudis (1996, 2016), Wingo (2004), Schmitt (2006), Duke et al. (2006), Schrunk et al. (2008), Anand et al. (2012), Badescu (2012), Crawford (2015) and Kornuta et al. (2019). It is not the intention to reiterate all this earlier work here. Rather, the purpose of this chapter is to present a geological and geographical inventory of lunar resources, together with a discussion of future work that will be required to improve our knowledge of this inventory, with emphasis on developments that have occurred since the publication of NVM I in 2006.

2. OVERVIEW OF LUNAR RESOURCES

All the naturally occurring chemical elements in the periodic table are present on the Moon, just as they are on Earth and every other Solar System body. However, their viability as potential resources depend on the value attached to them, the extent to which they have been concentrated by natural processes, and the ease with which they can be extracted and utilised in the space environment. Potential lunar resources differ significantly in the extent to which these criteria are likely to be satisfied, and these issues will be discussed in detail in the sections that follow. Broadly, however, lunar resources can be categorized as follows:

2.1. Major elements

The major rock-forming elements (e.g., O, Mg, Al, Si, Ca, Fe) are ubiquitous on the Moon, with concentrations ranging from several percent to several tens of percent (by weight) in lunar rocks and soils (e.g., Haskin and Warren 1991; Papike et al. 1998; Fig. 1). Additionally, Ti has typical concentrations of several percent in the high-Ti mare basalts. Of these elements, O is likely to be the most important initially from an ISRU perspective, with some of the metals possibly becoming important later as lunar development proceeds. Several of these elements are moderately concentrated in different lunar terrains (e.g., Al in anorthositic highland rocks, and Ti in high-Ti mare basalts; Fig. 2), and natural geological processes may have led to greater concentrations of some elements in geographically restricted localities (e.g., Haskin et al. 1993). Despite being ubiquitous, extraction of these elements will be energy intensive, owing to the need to break down their host crystal structures (discussed in Section 4 below).

2.2. Minor and trace elements

Several elements with average concentrations of ≪1 wt% in typical lunar rocks and soils may be useful from a resource perspective, especially if locations can be identified where natural geological processes (e.g., fractional crystallisation, hydrothermal processes or meteorite impacts) have produced local enrichments. Examples include U and Th, which may

eventually be useful in the context of space nuclear power systems, and the rare earth elements (REE), which might conceivably be of value for importation to Earth given the rapidly rising demand for these elements (McLeod and Krekeler 2017).
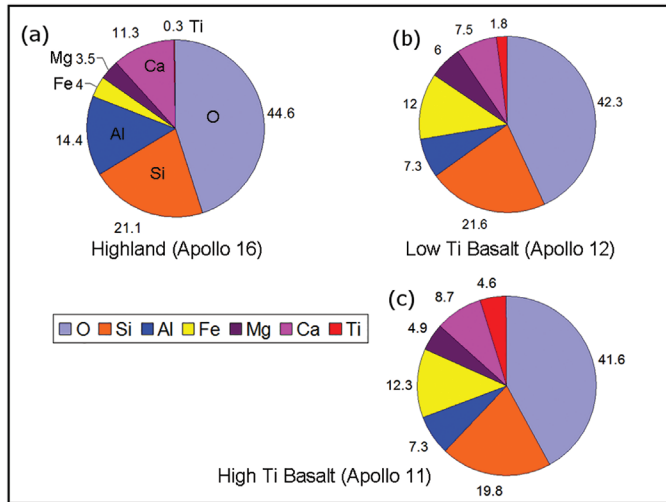
Figure 1. Elemental compositions of lunar soils: **(a)** lunar highland material (Apollo 16); **(b)** low-Ti basalts (Apollo 12); and **(c)** high-Ti basalts (Apollo 11). Based on data collated by Stoeser et al. (2010), and reprinted from Planetary and Space Science, Vol. 74, Schwandt C, Hamilton JA, Fray DJ and Crawford IA, 'The production of oxygen and metal from lunar regolith' p 49–56, Copyright (2012), with permission from Elsevier.
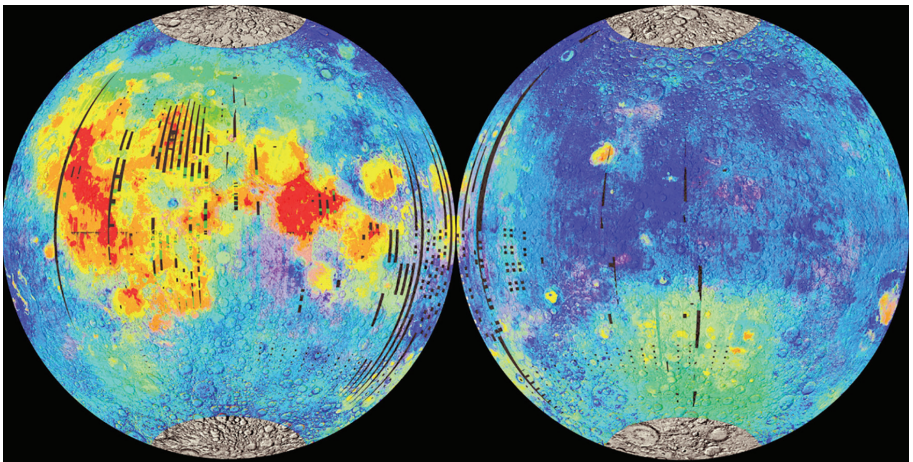
Figure 2. Petrologic map of the lunar nearside (**left**) and the farside (**right**), from Spudis et al. (2002; see also Zellner 2019). Broadly, **blue** areas correspond to the anorthositic highlands, **yellow** areas correspond to low-Ti mare basalts, and **red** areas to high-Ti basalts. The large **yellow/greenish** area in the southern hemisphere of the farside is the South Pole-Aitken Basin, where the colours mostly reflect the more Fe-rich nature of the basin floor. Image courtesy of Paul Spudis/LPI.

Volcanic processes may have concentrated a wide range of other useful elements. For example, glass and devitrified beads from pyroclastic deposits, discussed below as a potential source of water, are also enriched in iron and titanium oxides (e.g., Hawke et al. 1990).

In addition to a potential source for iron, titanium, and oxygen (Allen 2015), the glass and crystalline beads common in the larger lunar pyroclastic deposits also have surficial vapor-deposited coatings of volatile-element compounds that may prove to be valuable resources.

Elements such as C, N and P will be vital for food production if the Moon is ever to support a significant human population. Whereas P is contained in a range of lunar magmatic minerals (e.g., apatite, merrillite and monazite), C and N are very rare in lunar materials. However, the apparent detection of small quantities of NH_3 (~0.3 wt%), CO_2 (~0.1 wt%) and, possibly, CH_4 (~0.04 wt%) in the permanently shadowed floor of Cabeus crater by the LCROSS experiment (Colaprete et al. 2010) suggests that such regions may be useful sources of C and N in addition to water (discussed below). In addition, these elements may also have solar wind and meteoritic sources (see Section 2.4).

2.3. Water

Water is likely to be the most important near-term lunar resource, both for ISRU and for the later development of a cis-lunar economy. This is due to its multiple applications: (i) water is required for life-support, personal hygiene, energy storage in fuel cells, and as a solvent used in multiple industrial processes; (ii) it is a potential source of O_2 both for life support and rocket fuel oxidiser; and (iii) it is a potential source of H_2 for rocket fuel and as a reducing agent in industrial processes (including schemes to extract oxygen and metals by means of oxide-reduction processes). One of the most exciting developments in lunar science over the last two decades has been the realization that water and other volatiles may not be as scarce as had previously been thought. Following early speculations by Loewy and Puiseux (1897), predictions that water ice might exist in permanently shadowed regions (PSRs) in polar craters were made by Urey (1952), Watson et al. (1961a,b) and Arnold (1979). Supporting observations have been provided by neutron flux measurements by Lunar Prospector (Feldman et al. 1998, 2001) and radar observations (e.g., Nozette et al. 2001; Spudis et al. 2013), although the interpretation of both has been questioned (e.g., Campbell et al. 2006; Starukhina 2012; Fa and Cai 2013; Eke et al. 2014; Mitchell et al. 2018). Supporting indirect evidence for ~10 meter-thick ice deposits within south (but not north) lunar PSRs has recently been provided by statistical studies of the depth-to-diameter ratios of small (2.5–15 km diameter) impact craters (Rubanenko et al. 2019). Direct confirmation that water in some form exists at the lunar poles was provided by the LCROSS impact at Cabeus crater in 2009 (Colaprete et al. 2010), which indicated a water ice concentration of 5.6±2.9 wt% (1σ uncertainty) in the target regolith. In addition, Li et al. (2018) have reported infra-red reflectance measurements indicating the presence of surface ice in several PSRs, as well as in isolated patches in locally shaded regions within 20° of each pole.

In addition to evidence for water ice in PSRs, near-IR spectroscopy has indicated that high (>60º) latitude, but not permanently shadowed, lunar regolith also contains hydrated materials (Clark 2009; Pieters et al. 2009a; Sunshine et al. 2009; Li and Milliken 2017; Honniball et al. 2020). This OH/H_2O is thought to result from reduction of iron oxides in the lunar regolith by solar wind implanted hydrogen (e.g., Crider and Vondrak 2000; Ichimura et al. 2012). Working with Chandrayaan-1 Moon Mineralogy Mapper (M^3) data, Pieters et al. (2009a) estimated a water abundance of 10 to 1000 ppm, with the highest values observed at higher latitudes where it is cold enough to retain these volatiles; H_2O concentrations in the range 200–400 ppm were obtained independently by Honniball et al. (2020). However, the vertical extent, and thus total inventory, of these hydrated materials is unknown. Time variations in the strength of the 3 μm absorption feature suggest that the OH is dynamic and migrating across the lunar surface, possibly providing a source for ice trapped at the lunar poles (Sunshine et al. 2009; Wohler et al. 2017).

Water may also exist in endogenous magmatic materials that originated at depth within the Moon (e.g., Saal et al. 2008; Anand et al. 2014; McCubbin et al. 2015; Hauri et al. 2017). Although the Moon is generally volatile-depleted, recent analyses of water and other volatile species (e.g., F, Cl, S) in lunar samples suggest that water and other magmatic volatiles have

played an important role in lunar geological processes. The discovery of lunar magmatic water has necessitated a paradigm shift in our understanding of the history of water in the Moon, and has added new dimensions for ISRU considerations. Quantitative mapping of the abundance and distribution of indigenous lunar water (Milliken and Li 2017) shows a striking association with explosively emplaced volcanic deposits, and recent estimates suggest OH abundances of up to 750 ppm (Li and Milliken 2017).

Additional information on the distribution of water in the lunar surface has recently come from studies of lunar exospheric water released by meteoroid impacts (Benna et al. 2019). These observations indicate that much of the Moon is covered by a desiccated layer several cm thick, but that below this an average concentration of 220–520 ppm H_2O by mass may extend to a depth of at least 3 m. If confirmed, this result is potentially of great importance from a resource perspective because it implies a widespread source of water outside the polar regions or spatially restricted volcanic deposits.

2.4. Exogenously delivered materials

It is generally assumed that a large part, perhaps most, of the volatiles found at the lunar poles have been delivered to the Moon from external sources, for example through asteroid and comet impacts (see, e.g., discussion by Anand 2010) and/or from solar wind-derived hydrogen reduction of oxides and silicates in the regolith (Liu et al. 2012). This raises the possibility that other useful resources of exogenous provenance may be found on the lunar surface. It has been known since the return of the Apollo samples that the regolith retains a range of relatively volatile elements (e.g., H, He, C, N, Cl), with typical concentrations of a few tens of ppm (see Fegley and Swindle 1993 for a review). Some of these elements clearly have resource potential (e.g., H as a reducing agent, and C and N as feedstock for biological systems); the special case of ^3He (with a typical abundance ≤10 ppb) is discussed in Section 3.4. Laboratory experiments (e.g., Gibson and Johnson 1971) have determined that volatile elements can be extracted from the regolith by heating it up to ~700 ºC, but their low abundances imply that many cubic meters of regolith would need to be processed to yield useful quantities. If C and N-bearing volatiles such as NH_3 and CO_2 occur at higher concentrations in water ice at the lunar poles (Colaprete et al. 2010), the latter locations may be preferred as sources of these elements.

Although it has long been assumed that volatile elements in non-polar regoliths have been implanted in the regolith by the solar wind, recent studies have shown that most of the N, and possibly also the C and other elements, has a non-solar, probably meteoritic, origin (e.g., Füri et al. 2012; Mortimer et al. 2016). The lunar regolith also contains ~0.5 wt% native Fe, again largely from meteoritic sources (Morris 1980), which may also have resource applications. The identification of ubiquitous, albeit low-concentration, material derived from meteoritic sources in the lunar regolith raises the intriguing possibility that higher concentrations might be found at locations where meteorites have partially survived impact with the lunar surface. Wieczorek et al. (2012) suggested that lunar magnetic anomalies might be caused by the remains of metallic or chondritic meteorites, which, if confirmed, might represent exploitable resources of relatively enriched Fe, Ni, Co and the platinum group elements (Wingo 2004). It is also possible that some carbonaceous asteroidal material might survive impact with the lunar surface (Svetsov and Shuvalov 2015; Halim et al. 2021), and such impact sites might provide elevated concentrations of C and N (and possibly H_2O) that could help sustain biological processes (e.g., lunar agriculture).

2.5. The bulk regolith

The unconsolidated bulk regolith, which is likely to be the main feedstock for many lunar resource extraction processes, is also a potential resource in its own right. Readers interested in the physical properties of the lunar regolith are referred to the excellent reviews by Carrier et al. (1991), McKay et al. (1991), and Lucey et al. (2006). A helpful recent review of potential

regolith excavation techniques has been provided by Just et al. (2020). Potential applications of bulk regolith include: radiation shielding (a thickness of several meters will shield from all solar particle events and most galactic cosmic rays), micrometeorite shielding, and thermal insulation. In addition, processed regolith may lend itself as a feedstock for the additive manufacturing of structures on the lunar surface (e.g., Lim et al. 2017; Isachenkov et al. 2021), and microwave sintering may be possible for the production of roads and landing pads as part of a dust mitigation strategy (e.g., Srivastava et al. 2016; Lim and Anand 2019). These applications are discussed in more detail in Section 8.

2.6. The lunar near-surface environment as a resource

Although not normally considered as an economic resource, the natural lunar environment has properties which might be economically exploitable in the context of lunar development. For example, topographic highs at the lunar poles provide geographically restricted sites with access to direct sunlight for prolonged periods (Fig. 3), making them ideal locations for long duration solar-powered processes (for a location two meters above the surface, the highest illuminated such locations experience direct sunlight for between 82% and 92% of the time; Gläser et al. 2018). Natural caves and cavities in the lunar surface such as lava tubes (e.g., Blair et al. 2017) would provide shelter from cosmic radiation, micrometeorites, and diurnal temperature variations, and so may prove to be attractive locations for future human habitation in addition to being of scientific interest.
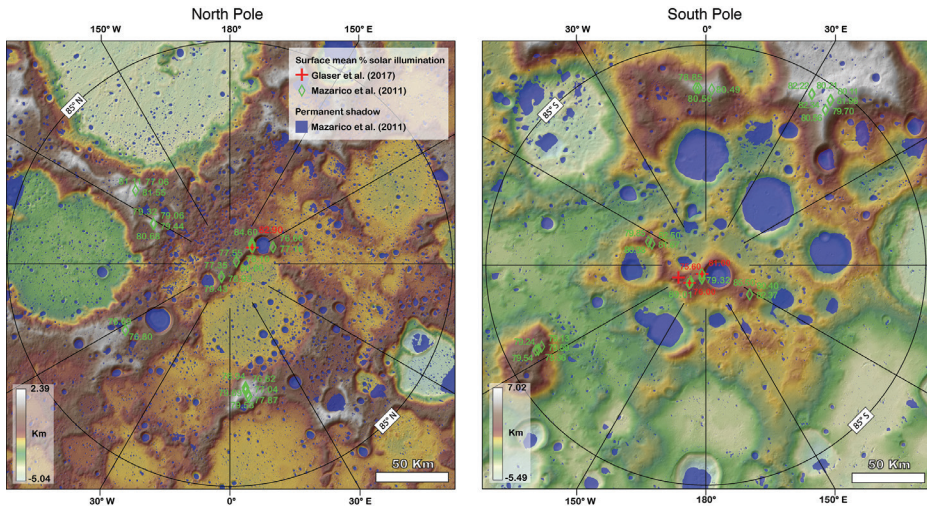
Figure 3. Areas at the lunar poles identified by Mazarico et al. (2011) and Gläser et al. (2018) that have > 75% mean annual solar illumination; 108 areas in total meet this criterion, but many are spatially clustered and consequently not all are labelled. Shaded blue areas are those in permanent shadow mapped by Mazarico et al. (2011) at 120 m/pixel. Elevation data are from LRO LOLA at 120 m/pixel.

The temperature gradients inherent to many lunar locales are also potentially exploitable as a resource. For example, the diurnal cycle could be combined with a thermal energy storage reservoir (composed of native or processed regolith) to produce a relatively simple thermal storage system. Such a system could be used to provide energy for low power activities, or implement the 'thermal wadi' concept (e.g., Wegeng et al. 2008; Climent et al. 2014) to keep surface assets warm during the lunar night. Furthermore, the hard vacuum, and night-time/polar cryogenic temperatures of the lunar environment may positively facilitate some industrial processes. These possibilities are discussed in more detail in Section 9.

3. LUNAR VOLATILES

Findings from lunar missions in the past two decades have brought about major advances in our knowledge of the abundance, distribution and sources of volatiles at the lunar surface. A brief summary was provided above (see also Hurley et al. 2023, this volume). Continued scientific investigations will be required to assess the contributions of different volatile sources, although from a resource perspective understanding the origins of lunar volatiles is less important than determining their abundances, accessibility and processability. In this section the nature of lunar volatile resources is explored in more detail, while a discussion of future mission requirements for better understanding their concentrations and distributions is deferred to Section 10.

3.1. Polar volatile deposits

Bolometric brightness temperatures derived from the Diviner Lunar Radiometer Experiment onboard NASA's Lunar Reconnaissance Orbiter (LRO) indicate that annual average temperatures in many PSRs are in the region of 40 K, with night-time temperatures in some regions as low as 25 K (Paige et al. 2010). McGovern et al. (2013) estimated that the cumulative area of permanently shadowed lunar surface is 13,361 km^2 in the northern hemisphere and 17,698 km^2 in the southern hemisphere; more recent modelling work by Hayne et al. (2021) has suggested that the total area occupied by PSRs, including very small (cm-km) examples, may be closer to 40,000 km^2, again with the southern hemisphere dominating. In both hemispheres most areas of permanent shadow occur pole-ward of 80° north or south latitude (Fig. 3), but small patches of permanent shadow are identified at latitudes as low as 58° in both hemispheres.

The PSRs near the lunar poles contain enhanced concentrations of volatiles because they are cold enough to retain surface deposits of many volatiles for billions of years (Watson et al. 1961a,b; Arnold 1979; Paige et al. 2010; Lawrence 2017). Sublimation is a strongly temperature-dependent loss process for volatiles in a vacuum, with a rate of ~1 mm/Ga for water ice at temperature of 100 K (Andreas 2007; Siegler et al. 2015). For the extensive areas in permanent shadow, the maximum temperature is lower than 100 K, inhibiting sublimation. This situation is likely to have persisted for 1–2 Ga (e.g., Arnold 1979; Siegler et al. 2015), so the existing PSRs have had environmental conditions conducive for retaining enhanced concentrations of water ice and other volatiles for a significant fraction of the age of the Moon. The presence of exposed surface ice in at least some regions of some PSRs is supported by recent observations of ultraviolet reflectivity (Hayne et al. 2015), near-infrared reflectivity (Fisher et al. 2017), and infra-red reflectance spectroscopy (Li et al. 2018), although the vertical extent of these deposits is currently unconstrained. A useful ranking of lunar PSRs, based on evidence of volatile content determined by different methods, has been provided by Brown et al. (2019).

The LCROSS impact into Cabeus crater revealed volatiles to be present in the ejecta plume produced by that experiment, with an H$_2$O concentration in the target regolith of 5.6±2.9 wt% (Colaprete et al. 2010). However, this value may not be representative of PSRs in general, and is significantly higher than those estimated from interpretations of polar neutron data (e.g., Teodoro et al. 2010: ~0.2–3.7 wt%; Sanin et al. 2017: ≤ 0.5 wt%) although the latter measurements may be affected by a surficial covering by hydrogen-poor material. It should also be noted that there is not a one-to-one correlation between PSRs and hydrogen concentrations as mapped by neutron measurements (Lawrence 2017), although such comparisons are hampered by the low spatial resolution of the neutron data. Reflectance measurements from orbit may be consistent with surficial enhancements of water frost in some PSRs, but probably not with thick deposits of surface ice (e.g., Haruyama et al. 2013; Lawrence 2017).

In addition to H$_2$O, the LCROSS experiment revealed a mix of volatile contents in the ejecta plume, including H$_2$, CO and Hg vapor observed by LRO LAMP (Gladstone et

al. 2010), and H_2S, SO_2, NH_3, CO_2, CH_4 and OH observed by the LCROSS shepherding spacecraft (Colaprete et al. 2010). Thus, these additional species, or their precursors, may also exist in enhanced concentrations in PSRs and may provide useful sources of C and N that are otherwise rare on the Moon. Observations of Ar in the lunar exosphere also suggest that a significant reservoir of Ar may be stored in lunar PSRs (Grava et al. 2015). Moreover, several elements not typically considered volatile, such as S and Hg, can become cold-trapped on the Moon at temperatures much higher than for water-ice. Hg in particular may be problematic: long known to be present in returned lunar samples, Hg was first predicted to be present at the lunar poles by Reed (1999) and later measured during the LCROSS impact experiment. The presence of Hg in lunar soils, either as metal or chemically bound (e.g., as halides), may make processing lunar ice for useable water more difficult.

Although many details about the abundance, physical form, composition, and distribution of volatiles in lunar PSRs will need to be better determined in order to implement ISRU, several factors indicate that harvesting those volatiles may be possible with only modest thermal inputs. In particular, the apparent thermal control of surface ice suggests that water might be liberated at temperatures >100 K (but again note that sublimation rates are a continuous function of temperature, and that this temperature is not a sharply defined threshold; see Figure 2 of Andreas 2007). Higher temperatures are likely to be required to extract water at rates relevant for ISRU. For example, Hibbits et al. (2011) found that water ice desorption in regolith simulants peaks between 140 and 170 K, and Kornuta et al. (2019) adopted a temperature of 220 K for their ice sublimation process. We also note that that a judgment of required extraction rates and temperatures will require knowledge of product demand, mining method, and other parameters that are outside the scope of this review.

Obtaining an estimate for the total inventory of water contained in lunar polar ice deposits is fraught with uncertainty. In particular, the relatively high value of 5.6±2.9 wt% H_2O found at Cabeus by LCROSS may not be representative of PSRs in general (Lawrence 2017), and the depth distribution of the water is unknown. As noted above, spatially deconvolved neutron data (Teodoro et al. 2010) yields an average water equivalent hydrogen (WEH) concentration for 12 PSRs of 1.4 wt%. Assuming a constant concentration within the uppermost two meters within the PSRs identified in Kaguya topography led Teodoro et al. (2010) to estimate a total inventory of ~$5{\times}10^{11}$ kg of water ice within lunar PSRs. Applying the same assumptions to the larger total area of PSRs found by McGovern et al. (2013) yields a comparable estimate ($7{\times}10^{11}$ kg H_2O). Rubanenko et al. (2019) also arrived at a figure of ~10^{11} kg based on their study of polar crater morphologies. However, it is difficult to know how accurate such estimates will prove to be. On the one hand, not all PSRs may contain a significant quantity of ice (Teodoro et al. 2010; Sanin et al. 2017; Lawrence 2017). On the other hand, ice is likely to be stable at depths of a few tens of cm in polar regoliths outside the PSRs (Paige et al. 2010), so the total quantity of water ice present on the Moon could be larger than estimates based only on the areas of the PSRs themselves. Obtaining better estimates of the concentration of water ice within (and around) PSRs, its physical form, and the total lunar polar water inventory are therefore important objectives for future research.

Lunar PSRs potentially store large quantities of volatiles, in high concentrations and in forms that in principle appear readily extractable. Cannon and Britt (2020) have recently developed a geological model for lunar polar ice deposits at scales appropriate for mining activities, and find that impact gardening is likely to homogenize deposits on meter to hectare scales. Consideration of the technical requirements for extracting and processing these volatiles is beyond the scope of this chapter, and interested readers are instead referred to the recent detailed technical study by Kornuta et al. (2019). It is, however, clear that PSRs will present unique challenges to extracting resources, including extremely low (and variable) surface temperatures, permanent darkness, a heterogeneous distribution of resources,

possible toxic contamination of volatiles, and uncertain geotechnical properties. It must also be recognized that unanticipated problems may arise once *in situ* operations in PSRs begin. And, of course, PSRs may not be conveniently located adjacent to the localities which are attractive for planned exploration activities. For these reasons, locating more widespread sources of lunar volatiles is also desirable.

3.2. Non-polar volatiles

Near-infrared (NIR) reflectance spectroscopy, conducted by instruments on orbiting or flyby spacecraft, is well-suited for the detection of diagnostic OH/H_2O absorptions around 3 μm wavelength. Observations revealing the presence of surficial OH/H_2O in non-polar regoliths have been obtained by various NIR observations (Clark 2009; Pieters et al. 2009a; Sunshine et al. 2009; Li and Milliken 2017) and supported by UV (Lyman alpha) absorption-line measurements (Hendrix et al. 2019). However, in the context of ISRU, it is important to appreciate that these measurements probe only the uppermost (~1 mm) regions of the lunar surface. Furthermore, a number of processes are known to complicate the interpretation of NIR data, including thermal radiation and viewing geometry.

Li and Milliken (2017) applied new thermal corrections that allowed more reliable interpretation of datasets obtained by the M^3 instrument on Chandrayaan-1. The OH abundance generally increases as a function of latitude, from less than 100 ppm for the ±30° latitude zone, to maxima of ~500 and ~750 ppm for southern and northern hemispheres respectively (Li and Milliken 2017). The corresponding global lunar water reservoir, assuming a uniform mixing into the uppermost 1 m of regolith (which needs to be confirmed but is consistent with the recent results of Benna et al. 2019), was estimated to be ~1.2×10^{11} kg. Soil maturity is also found to be a factor, with mature soils enhanced in water content by up to factor ~3 (Li and Milliken 2017). Soil composition is not found to be a contributory factor, with the exception of enhanced water content associated with magmatic materials (see Section 3.3). Clear evidence is found for diurnal variations in surface OH/H_2O concentrations of ~200 ppm during a lunar day, with the effect being stronger in the 30° to 60° latitude range and the highest concentrations (>400 ppm) observed in the morning local time. Although these diurnal variations may prove to be entirely surficial, and hence of marginal significance for resource extraction, it is pertinent that the loss of water is most likely associated with temperature, suggesting that careful attention to ISRU process design will be important to minimize losses through unintentional heating of feedstock during processing. It may also be possible to harness the local temperature cycles to enhance volatile collection efficiency. The apparently strong latitude dependence implies that the availability of water for extraction may be a driver for landing site location, although Benna et al. (2019) have argued that even equatorial regoliths may contain several hundred ppm H_2O below a desiccated surface layer a few cm thick.

In addition to considering concentrations within the regolith, it is necessary to consider the form in which the target volatiles are present, as this can strongly influence the energetics of the extraction process. The rate of water ice desorption becomes sufficiently high to be of practical utility at temperatures as low as ~150 K (Hibbits et al. 2011), whereas chemisorbed molecular water is released over a wider range of temperatures, typically up to 450 K (Hibbits et al. 2011; Poston et al. 2013). For comparison, oxygen bound within minerals can be released through a variety of reduction processes (see Section 4, below), but requires much higher temperatures, typically in the range 1200–1900 K (e.g., Taylor and Carrier 1993; Hepp et al. 1994; Schlüter and Cowley 2020).

3.3. Pyroclastic and other magmatic sources of volatiles

Magmatic processes on the Moon, including those associated with explosive or pyroclastic volcanism, have resulted in surface deposits enriched in volatile elements. Although the Moon is generally thought to be volatile-depleted, recent analyses of lunar samples originating from depth

suggest that water and other magmatic volatiles (i.e., F, Cl, S, Zn) have played an important role in lunar geologic history (e.g., Saal et al. 2008; Hauri et al. 2011, 2015, 2017; Anand et al. 2014; McCubbin et al. 2015). The abundances of these volatiles in lunar pyroclastic glasses range from ~5–13 ppm H_2O, 9–17 ppm Cl, and 282–490 ppm S in Apollo 17 high-Ti orange glasses, and ~0.4–30 ppm H_2O, 2–10 ppm F, 0.03–0.50 ppm Cl and 114–270 ppm S in Apollo 15 very-low-Ti green glasses, to the highest volatile abundances observed at 17–46 ppm H_2O, 29–40 ppm F, 1.2–2.0 ppm Cl and 518–576 ppm S in Apollo 15 low-Ti yellow glasses (Saal et al. 2008). Radial variations in the abundance of these volatiles within individual glass beads support the argument that they are indigenous, but were likely subjected to degassing upon eruption.

Studies of olivine crystals in high-Ti orange glass beads (Hauri et al. 2011) have found H_2O concentrations of 270–1200 ppm in melt inclusions. These H_2O contents are correlated with other elements (~37–72 ppm F, ~450–880 ppm S, and ~1.5–2.4 ppm Cl) that are considered to be representative of a primary lunar magma. In lunar basalts, apatite is the only mineral found to contain significant levels of OH (Jolliff et al. 2006b; McCubbin et al. 2015), with abundances generally in the range ~100–7000 ppm H_2O (e.g., Tartèse et al. 2013). By contrast, apatite grains in other lunar rock types (e.g., the magnesian and alkali suites, and KREEP-rich impact melts) tend to have lower water contents (~100–1600 ppm; as summarized in McCubbin et al. 2015). Based on these and similar studies, Hauri et al. (2015, 2017) concluded that the abundance of water in the bulk silicate Moon probably lies in the region of ~100–300 ppm, comparable to estimates for the mantle source regions of terrestrial Mid-Ocean-Ridge Basalt.

Quantitative mapping of the abundance and distribution of lunar indigenous water shows a striking association with explosively emplaced volcanic deposits, with local enrichments of up to 300–400 ppm H_2O (Milliken and Li 2017). These pyroclastic deposits are fine-grained mantling units that extend from their source vents to many hundreds of km (Head and Wilson 2017). A range of small (~10 km^2) to very large (~50,000 km^2) lunar pyroclastic deposits have been recognized as rock-free, glass-rich units (Gaddis et al. 2003). At least one of the larger deposits (at Rima Bode) has a thickness ranging from ~4 to 13 m (Huff et al. 2015). Glass and devitrified beads from many of the larger pyroclastic deposits are also enriched in iron and titanium oxides (e.g., Hawke et al. 1990). In addition to a potential source of Fe, Ti and O (Allen et al. 2015), the glass spherules and crystalline fragments common in the larger lunar pyroclastic deposits also have surficial vapor-deposited coatings of volatile-element compounds (more than 25 species have been identified, including Au, Ag, Cu, Cd, F, S, Zn; e.g., McCubbin et al. 2015) that may also prove to be valuable resources on the lunar surface.

3.4. Solar wind and/or micrometeorite-derived volatiles

Because the Moon has almost no atmosphere or global magnetic field, the solar wind impinges directly onto the lunar surface. As a consequence, solar wind particles are implanted into regolith grains. The elemental composition of the solar wind is predominantly H and He, with the occurrence of heavier elements generally decreasing with increasing mass. Volatile elements found implanted in the lunar regolith, generally with concentrations in the range 30–100 ppm (μg/g), mainly consist of H and noble gases (He, Ne, Ar, Ke, and Xe) together with C, N, F, and Cl (see review by Fegley and Swindle 1993, and references cited therein; also Curran et al. 2020). As noted in Section 2.4, it appears that much of the N found in lunar soils, and possibly also C and other elements, may have a meteoritic origin (e.g., Füri et al. 2012; Mortimer et al. 2016). From a resource perspective, the ultimate origins of volatiles trapped within the lunar regolith are of importance primarily insofar as they may affect their distribution and concentration.

Analyses of lunar samples from the Apollo and Luna missions show that the abundance of solar wind-implanted volatiles depends on regolith grain size, maturity, solar wind flux, surface location, and composition (e.g., Johnson et al. 1999; Fa and Jin 2007). The monthly average solar wind flux varies with surface location for two reasons: higher latitudes receive a lower flux, and

the Moon spends about five days per month in the tail of the Earth's magnetosphere which affects the solar wind flux on the near-side hemisphere. As the implantation depth of the solar wind is less than 1 μm, solar wind volatiles tend to be concentrated in the finer grain sizes fractions of lunar soils because of the larger surface-to-volume ratio. Although only materials within 1 μm of the surface can be implanted with solar wind particles, subsequent impact gardening results in a roughly constant distribution within the uppermost few meters of the regolith (Fegley and Swindle 1993). Additional factors affecting the volatile abundance in lunar soils are their maturity, which is a measure of the time that the soil has been exposed to the solar wind and micrometeorite bombardment, and their mineralogy. For example, He and Ne contents are found to be ~10 to 100 times higher in ilmenite than in other minerals (e.g., Fegley and Swindle 1993). The extent to which colder, high-latitude, regoliths retain solar wind and/or meteoritic volatiles remains to be determined, although the evidence for the retention of other volatiles at high latitudes (see Section 3.2 above) suggests that this could be important.

Maturity and composition of the lunar surface can be measured by remote sensing techniques, and monthly averaged solar wind flux can be modeled by considering solar wind incident direction and shielding of the nearside by the Earth's magnetotail. For example, Fa and Jin (2007, see their Fig. 6) combined Apollo sample measurements with Clementine UV-VIS data to estimate the distribution of ^{3}He over the lunar surface, finding that concentrations as high as 20 ppb may occur in Mare Tranquillitatis and Oceanus Procellarum. Similar results have been obtained by Kim et al. (2019), who additionally estimated high (i.e., ≥20 ppm) ^{3}He concentrations in Mare Moscoviense and the craters Grimaldi and Riccioli.

To estimate the global inventory of solar wind-implanted volatiles for future resource utilization, it is necessary to know the regolith thickness and how the volatiles are distributed with depth. Regolith thickness can be estimated locally using geophysical measurements, regional impact crater morphologies, and global radar and microwave remote sensing techniques (e.g., Fa and Wieczorek 2012). From these methods, the typical regolith thickness is found to be ~4–5 m in the maria and ~10–15 m in the older highland regions (e.g., Shkuratov and Bondarenko 2001; Fa and Jin 2010a). Apollo drill core samples revealed essentially constant volatile concentrations to depths of 1–3 m (Fegley and Swindle 1993). An upper limit of the global inventory of solar wind-implanted volatiles can therefore be estimated if a uniform depth distribution of solar wind volatiles within the regolith is assumed. For example, using the regolith thickness estimated from China's Chang'E-1 microwave radiometer (4.5 m over maria and 7.6 m over nonpolar highlands regions), the global inventory of ^{3}He was estimated as being 1.70×10^9 kg (8.64×10^8 kg over the nearside, and 8.33×10^8 kg over the farside) for a uniform depth distribution (Fa and Jin 2010b). Total inventories of other solar wind-derived volatiles can be estimated in a similar way, and would be expected to be between two to three orders of magnitude higher.

Much previous speculation has centered on the possible use of solar wind-derived ^{3}He in the lunar regolith as a fuel for future nuclear fusion reactors (e.g., Schmitt 2006), although ^{3}He-based nuclear fusion has not yet been demonstrated to be a viable source of energy. Moreover, the concentration of ^{3}He in the lunar regolith is very low: in the range 2–10 ppb in Apollo soil samples (Fegley and Swindle 1993) and perhaps 20 ppb in mature high-Ti basaltic soils (Fa and Jin 2007). It is therefore far from clear that significant exploitation would be economic in terms of mining ^{3}He on the Moon and exporting to the Earth (see discussion by Crawford 2015). That said, any scheme designed to extract ^{3}He from the lunar regolith would also yield much larger (by at least two orders of magnitude) quantities of other solar wind-implanted volatiles of possible economic benefit (principally H and ^{4}He). For this reason, there is a good case for implementing a pilot regolith volatile extraction scheme on the Moon to assess the possible long-term economic value of solar wind implanted volatiles.

Solar wind (and/or meteoritic) volatiles may be extracted from the regolith by heating it to several hundred degrees Celsius. For example, most H and He is extracted over the temperature

range 300–700 °C, with heavier elements requiring higher temperatures (Gibson and Johnson 1971; Fegley and Swindle 1993). Note, however, that processing large volumes of regolith will be required to extract useful quantities. For example, H has a concentration of ~50 ppm in lunar soils (Fegley and Swindle 1993), which implies that heating a cubic meter to ~700 °C would release ~0.08 kg of H.

4. OXYGEN FROM SILICATE MATERIALS

Oxygen is one of the most useful resources that can be extracted from lunar surface materials, initially for life support and then, as operations expand, as oxidiser for fuel. Based on requirements for the international space station, a three-person crewed lunar outpost would require 10^3 kg oxygen/year (Jones and Kliss 2010), whereas more ambitious operations where oxygen is also used for orbital assets might require ~10^6 kg/year (Christiansen et al. 1988). Oxygen extraction from frozen water ice in PSRs is a relatively low-energy and conceptually simple process (see Section 3.1). However, even if assessed by the next phase of lunar missions (e.g., George et al. 2012; Barber et al. 2017) to be a viable resource, there will still be serious obstacles to be overcome owing to the very low temperatures and geographical restrictions. Water derived from polar ice may turn out to be a limited resource, useful for initial polar operations but not sustainable long term. It may also not be ideal for human operations far from the lunar poles.

Alternatively, oxygen is widely present on the Moon (Fig. 1), albeit tightly bound within silicates and metal oxides. Over twenty different methods have been suggested for lunar oxygen extraction from lunar minerals (e.g., Taylor and Carrier 1993; Hepp et al. 1994; Schrunk et al. 2008; Schwandt et al. 2012; Schlüter and Cowley 2020). Each process has advantages and disadvantages with respect to the feedstock used, resupply mass, process complexity and energy required, although most require temperatures in the range 900 to 1600 ℃ (Hepp et al. 1994; Schlüter and Cowley 2020). In addition, although often neglected, these processes will rely on varying levels of feedstock beneficiation for mineral separation and/or particle size sorting, and on the development of techniques for mitigating the effects of unwanted contaminants in the feedstock.

Despite over 40 years of laboratory studies, for many of these processes the technology readiness level (TRL) has remained low (typically in the region of 1–2). In 2005 NASA initiated an ISRU project as part of the Exploration Technology and Development Program, with the aim of increasing the TRL of ISRU technologies to level 6 (Moore and Peri 2007). Three oxygen extraction techniques were selected for further research: hydrogen reduction of iron oxides; carbothermal reduction of regolith; and molten oxide electrolysis (Table 1; Sanders and Larson 2013):

- Hydrogen reduction is a process which heats oxides (generally Fe-Ti oxides) to ~900 °C in the presence of H. The water produced is electrolysed to generate H and O, where the H is fed back into the reactor. This simple and well understood process operates at relatively low temperatures, thus reducing energy requirements. However, it is limited to locations with high Fe-Ti content (e.g., mare basalt regions), and has relatively low yields (Table 1).

- Carbothermal reduction of regolith requires heating of regolith past its melting point to >1600 °C in the presence of methane. Methane cracks to produce C and H, where the C reacts with O from silicates to produce carbon monoxide. Carbon monoxide and H are then reacted over a catalyst to produce water and methane. Methane is re-used in the reaction, and water is electrolyzed to produce O and H. This process has higher O production efficiencies than H reduction of iron oxides, and is not limited to a specific geological setting. However, the high temperatures involved require a more complex system to manage molten regolith.

- Molten oxide electrolysis also utilises lunar regolith that is heated past its melting point where it is electrolyzed. Oxygen gas is released from metal and non-metal oxides, providing even higher O extraction efficiencies than carbothermal reduction. Pure Fe, Si and other metals can also be produced during this process. However, the molten regolith must be managed, along with the molten metals and high temperature pure O, complicating the system design.

One of the outcomes of this project was end-to-end field test demonstrations of H reduction and carbothermal reduction processes, including regolith feed and removal, regolith mixing and heating with hydrogen/methane, water vapor removal and collection, water electrolysis, and oxygen storage. Although research was also performed on molten oxide electrolysis, a field test system was not produced. This work led to an increase in the TRL with technology development and demonstration (Table 1) of the three oxygen extraction processes studied (for details see Sanders and Larson 2013).

Table 1. Oxygen extraction efficiencies and TRL Levels for ISRU concepts reported by Sanders and Larson

Extraction technique	Oxygen yield per 100 kg of lunar regolith	TRL before ISRU project	TRL after ISRU project
Hydrogen reduction of iron oxides	1–3 kg	2–3	5
Carbothermal reduction of regolith	10–20 kg	2–3	5
Molten oxide electrolysis	20–30 kg	2	3

Historically, one of the most studied hydrogen reduction processes involves the reduction of the iron-titanium oxide ilmenite ($FeTiO_3$; e.g., Zhao and Shadman 1993, Li et al. 2012; Jamanca-Lino 2021):

$$FeTiO_3 + 2H \rightarrow Fe + TiO_2 + H_2O \tag{1}$$
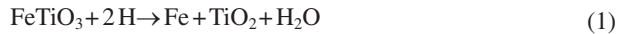
Ilmenite generally comprises 10-20% by volume of high-Ti mare basalts (e.g., Warner et al. 1978; Chambers et al. 1995; Papike et al. 1998; Hallis et al. 2014), making it especially attractive as a source of oxygen in those regions (e.g., Jamanca-Lino 2021). Chambers et al. (1995) noted that ilmenite concentrations in crushed basalts and immature to sub-mature soils are comparable to those in the parent rocks, but that ilmenite concentrations are reduced in mature soils owing to agglutinate formation, making such soils less suitable as feedstocks for O production. On the other hand, Chambers et al. (1995) also showed that magnetic beneficiation of lunar soils could increase ilmenite concentrations by about a factor ~2. Although most attention has focused on ilmenite, it is important to realise that O can also be released from other common lunar minerals through reduction of Fe^{2+} by H, and that a first-order estimate of oxygen production potential of lunar soils can be estimated from measurements of their total Fe content (Allen et al. 1996).

A large-scale ilmenite reduction reactor has been developed at the Plataforma Solar de Almeria (PSA) research centre in Spain, where the fluidized bed reactor has a capacity of 25 kg of regolith and utilizes direct solar thermal heating to heat ilmenite-bearing feedstock in the presence of hydrogen. Whilst still in the early stages of development, the system aims to generate oxygen at a rate of ~5×10^3 kg/year (Denk and Gonzales Pardo 2017). Use of direct solar energy to provide the high temperatures required for oxygen extraction from lunar materials is attractive because it will avoid problems and inefficiencies associated with electrical power conversion, and some conceptual work on such systems in a lunar setting has already been performed (e.g., Nakamura and Senior 2008).

Novel oxygen extraction techniques continue to be proposed. Recently, two different electrolysis methods have been developed using molten salts as electrolytes to reduce the high operating temperature of 1600 °C to less than 1000 °C. The first, known as the 'FFC-Cambridge' process (Fray et al. 1999), uses a cathode made from compressed sintered regolith which is immersed in a calcium chloride ($CaCl_2$) bath at a temperature of ~900 °C (Schwandt et al. 2012; Lomax et al. 2020). Oxygen ions from the metal oxides in the cathode transfer through the molten salt to be liberated as oxygen molecules at the anode. The second recent proposal involves a two-stage process where regolith is added to an aluminium and cryolite (Na_3AlF_6) salt mixture, at a temperature of 980 °C, to remove Si, Fe and Ti, followed by electrolysis (in a similar fashion to a Hall Héroult cell) to produce aluminium and oxygen (Liu et al. 2017; Xie et al. 2017). These methods could use appropriately sized lunar soils as a feedstock, so are not highly landing site specific, although reclaiming the electrolytes would need to be evaluated.

Since NVM I was published, there have been clear advances in several oxygen production techniques, although there may be no single process that is suitable for all locations and scenarios on the lunar surface. The next step will be to perform ISRU demonstrations on the lunar surface itself. For example, ESA's ProSPA payload will attempt to perform a small scale ilmenite reduction demonstration in the mid-2020s (Barber et al. 2017; Sargeant et al. 2020). However, further TRL increases will be needed before large scale ISRU demonstrations will significantly contribute to the oxygen supplies of a human mission. In addition, space agencies will need to devise strategies that provide on-ramps for ISRU-derived oxygen into mission planning, so as to create demand and gradually introduce dependency on local resources.

5. METALS AND OTHER COMMON ELEMENTS

5.1. Metallic ores/deposits resulting from magmatic and hydrothermal processes

Numerous types of terrestrial ore deposits result from the combination of magmatic differentiation, which concentrates incompatible elements in silicate melts, and the interaction of these melts with hydrothermal fluids capable of leaching, transporting and re-concentrating these elements (e.g., Seward et al. 2013). Because the Moon has been traditionally viewed as a volatile-poor body, magmatic concentration mechanisms have previously been considered when dealing with possible lunar resources (e.g., Papike et al. 1991; Duke et al. 2006). Magmatic differentiation of lunar magmas may be accompanied by large enrichment in incompatible trace elements, such as the rare earth elements in KREEP-rich magmas (see Section 6, below). However, evidence gathered during the past decade now suggests that the Moon may contain significant quantities of water and other volatile species distributed both inside the Moon and in the lunar regolith (see Hurley et al. 2022, McCubbin et al. 2023, both this volume), prompting us to investigate the possible role of these volatiles in the context of lunar resources.

There is growing evidence for hydrothermal activity and metasomatism in lunar rocks, including the presence of akaganeite [FeOOH] and lawrencite [$FeCl_2$] in Apollo 16 'rusty rock' 66095 (Shearer et al. 2014), magnetite [Fe_3O_4] in Apollo 16 sample 60016 (Joy et al. 2015), sub-solidus reduction textures in Apollo 14 sample 14053 (Taylor et al. 2004), exceptionally large apatite crystals in Apollo 17 granulite 79215 (Treiman et al. 2014), and sulfide replacement textures in Apollo 16 breccias (Shearer et al. 2012). In most cases it seems that the metasomatic fluids were rich in S and/or Cl, which are two very efficient ligands in promoting metal transport (Seward et al. 2013). Therefore, localized hydrothermal activity on the Moon may have resulted in transport and concentration of important metals such as Ni, Co, Se, Cu, Zn, Pb and Sb. Prospecting strategies akin to those used on Earth, combining high resolution remote sensing and geological surveying and sample analysis on the ground, will be required to locate any lunar hydrothermal deposits and assess their economic potential.

Lava-fountain volcanism may have provided another source of metals, since pyroclastic deposits are widespread across the Moon's surface (Gustafson et al. 2012), and pyroclastic glass beads are characterized by large enrichment (by factors of ~ 5–500) of metals such as Fe, Ni, Zn, Ga, Ge, Pb, Cd, Te, In, Hg and Au on their surfaces (Duke et al. 2006). Modeling work by Renggli et al. (2017) suggests that metals deposited near the eruption temperature (~1450 ºC) would be found as metallic species. This suggests that pyroclastic beads deposited close to the volcanic vent sites would be mainly coated with metallic species, whereas beads deposited further away are more likely to be coated with metal-bearing sulfides. Therefore, indigenous metals potentially interesting in terms of resources may be found concentrated near volcanic vents.

Finally, impact-induced devolatilization of icy regolith could drive formation of hydrothermal systems in the sub-surface lasting for a few years to a few decades (Stopar et al. 2018). Eruption of hot basaltic lava flows on top of an icy lunar regolith may have similar effects (Rumpf et al. 2013). If exposed to flowing liquid water liberated in such contexts, small glassy phases such as agglutinates and pyroclastic glass beads could be readily altered. Thus, such short-lived hydrothermal systems may conceivably be an efficient concentration mechanism for these trace metals already enriched on the surface of pyroclastic beads.

5.2. Fe, Al, Ti as residua from oxygen production processes

Oxygen production on the Moon is likely to be the main driver for ISRU during the early development of a sustainable human presence and may provide additional metal concentration processes. For example, in the case of ilmenite reduction by hydrogen, the residue is an intimate mix of iron and titanium dioxide. As in commercial production on Earth, smelting this residue will produce pig iron and a titanium slag, the raw material for titanium production.

As discussed in Section 4, molten regolith electrolysis, whereby regolith is melted at ~1600 ºC and electrolyzed to produce oxygen, will also yield metals as a by-product. However, the high temperatures required can cause problems for containment and electrode life. Progress has been demonstrated on lunar simulants (Sibille et al. 2009) and cold-walled reactors using regolith as an insulator have been modeled (Schreiner et al. 2015). The use of regolith as its own containment material has also been demonstrated for oxygen production by carbothermal reduction (Gustafson et al. 2010). Alternatively, fluoride salts can be added to reduce the operating temperature to less than 1000 ºC (Hall-Héroult cells; see Totten and MacKenzie 2003), which could be used to produce Al. On Earth the feedstock is normally bauxite, but anorthite can also be used which is more relevant in the lunar context. Finally, the FFC-Cambridge electrolysis process (Fray et al. 1999) occurs between a metal oxide cathode and an inert anode placed in a molten calcium chloride salt (e.g., Schwandt et al. 2012; Chen et al. 2000; Lomax et al. 2020). In theory, using sintered anorthosite as the cathode should produce a layer of aluminum, in addition to producing oxygen at the anode. The method has successfully demonstrated the production of a Fe-Ti alloy from a sintered ilmenite cathode (e.g., Schwandt et al. 2012; Lomax et al. 2020; see also Liu et al. 2017; Xie et al. 2017). Recently, Ellery (2016) and Ellery et al. (2017) have investigated combining the FFC-Cambridge process with 3D printing to produce a diverse range of metal products, including structures, motors and electronic components.

5.3. Silicon

Efficiently mining and processing Si *in situ* on the Moon could one day become important for the production of solar cell arrays generating electricity from the energy provided by sunlight (Duke et al. 2001; Ignatiev and Freundlich 2012; Lewis-Weber 2016). The Si content of lunar soil and regolith material is roughly constant at ~20 wt% (Fig. 1). Some of the extraction techniques that have been proposed include electrolysis of molten regolith, electrolysis of solid regolith, or fluorination (e.g., Duke et al. 2006; Landis 2007; Schwandt et al. 2012).

One of the crucial issues around Si mining on the Moon is whether high purity Si can be efficiently produced, since metallurgical grade Si is not acceptable for solar cell operation. Therefore, processes would need to be selected based on the requirement that Si has to be produced in a form allowing easy purification. In theory, *in situ* production of Si from the regolith should be feasible using the electrolysis processes described above for other metals such as Fe and Al (e.g., the FFC-Cambridge process; Schwandt et al. 2012), but as far as we are aware it has not been demonstrated that high purity Si can be recovered using such processes.

Fluoride extraction is an alternative process (e.g., Seboldt et al. 1993; Landis 2007). As detailed by Landis (2007), fluorine would be brought to the Moon as potassium fluoride (KF) which would provide F and K once electrolyzed, with both being utilized as reactants in the process. The first step involves heating a mixture of regolith and F to around 500 ºC, which replaces O in silicon dioxide molecules to form silicon tetrafluoride, following the reaction:

$$SiO_2 + 2F_2 \rightarrow SiF_4 + O_2 \qquad (2)$$

Note that this reaction yields O_2 as a by-product, which could supplement the oxygen production processes described in Section 4 above. Once liquefied at 187 K, the SiF_4 could then be distilled to remove trace contaminants. Further reduction using K would allow recovering elemental silicon, following the reaction:

$$SiF_4 + 4K \rightarrow Si + 4KF \qquad (3)$$

If this process turns out to yield unsatisfactory levels of K contamination, alternative processes of SiF_4 decomposition to $Si + 2F_2$ may be possible. Finally, this process would also produce Fe-, Mg-, Ca- and Al-bearing fluoride salts from typical regolith samples, which could then be further processed to recover these metals. There are practical difficulties in the use and storage of fluorine, but the use of fluorine compounds has been well-established in industry for decades (see, e.g., Landau and Rosen 1947) and its potential use on the Moon should not be discounted (Seboldt et al. 1993).

Finally, we note that Si (as well as Fe and other common metals) have been concentrated from regolith simulants using genetically modified microorganisms (Lehner et al. 2019), and this 'biomining' approach to ISRU might complement other methods (e.g., Olsson-Francis and Cockell 2010; Klas et al. 2015; Loudon et al. 2018; Cockell et al. 2020; Castelein et al. 2021).

6. RARE-EARTH AND ASSOCIATED ELEMENTS

The rare earth elements (REE; usually defined as the 15 lanthanides, spanning lanthanum to lutetium in the periodic table, plus scandium and yttrium) exhibit a wide range of industrially important optical, electrical, magnetic and catalytic properties (e.g., Chakhmouradian and Wall 2012). In spite of their name, Earth itself has abundant REE deposits, although significant geopolitical and environmental questions arise regarding their extraction and marketing (e.g., Hatch 2012). It seems unlikely that exporting lunar REE to Earth will be economically viable for the foreseeable future (unless the *environmental* costs of REE extraction on Earth become prohibitive, see discussion by Crawford 2015). Lunar REE mining may therefore have to wait until off-Earth markets are developed.

The REEs, together with other incompatible trace elements (ITEs), including K, P (collectively referred to as KREEP), Th and U, may have become concentrated by lunar geological processes (e.g., McLeod and Krekeler 2017). After ~99% of Lunar Magma Ocean (LMO) crystallization, the remaining melts would have been enriched in ITEs due to their incompatibility in common lunar minerals (e.g., Warren 1985; Gaffney et al. 2023, this volume).

This late-stage residuum of LMO differentiation is known as the urKREEP reservoir ("ur" meaning primitive), with which KREEP signatures in lunar lithologies are associated (Warren and Wasson 1978; Warren 1985, Neal and Taylor 1989), although samples of the primordial urKREEP reservoir have not yet been identified.

## 6.1. Lunar REE mineralogy and chemistry

The majority of ITEs on the Moon are closely associated with the Procellarum KREEP Terrain (PKT), on the north-west part of the lunar nearside (e.g., Jolliff et al. 2000). Beneath the Oceanus Procellarum region, the volume of KREEP-rich lithologies has been estimated based on the abundance of radioactive elements at 2.2×10^8 km^3, with potentially ~2.25×10^{14} to 4.5×10^{14} kg of REE reserves associated with it (Zou et al. 2004).

The REE budget of the Moon is dominated by the minor and trace mineral phases into which the REEs readily partition. The lunar mineral phase which to date has been shown to contain the highest total REE abundances is monazite $[(Ce,La,Nd,Th)PO_4]$. Monazite is rare among lunar lithologies, but has been found as small inclusions (~10 μm × 3 μm) within pyroxene grains from Apollo 11 (10047,68; Frondel 1975), impact melt breccias (Jolliff 1993), in Apollo 17 monzogabbro fragments (Jolliff et al. 1996), Luna 24 soils (Kartashov et al. 2006), and an Apollo 12 granite (Seddio et al. 2014). Seddio et al. (2014) reported 30 wt.% of REE oxides (REO) in the monazite grains they analyzed, with corresponding 23 wt. % ThO$_2$, and 4.5 wt. % UO$_2$. In addition to apatite, merrillite, and monazite, another high REE-abundance, yet rare, REE-rich phase which has been identified in lunar samples is yttrobetafite $[(Ca,Y,U, Th,Pb,REE)_2(Ti,Nb)_2O_7]$. To date this has been found in Apollo 14 breccia 14321,1494 ("Big Bertha") for which Meyer and Yang (1988) reported 12.3 wt. % REEs with 4.3 wt. % UO$_2$, and in the Apollo 12 granite studied by Seddio et al. (2014) where 11.3 wt.% REOs are reported along with 5.95 wt. % ThO$_2$ and 3.34 wt. % UO$_2$.

Figure 4 compares REE concentrations of some lunar lithologies with terrestrial crustal reservoirs and terrestrial ore deposits. The Apollo 14 ITE-enriched quartz monzodiorite (QMD) and whitlockite-bearing monzogabbro display ~10–20 times higher REE abundances than terrestrial crustal reservoirs, although these are still much lower than the concentrations than found in terrestrial REE ores. For a mineral deposit to be classified as an ore the cost of extraction must be economically justifiable. This therefore requires the element(s) of interest to be present in abundances high enough, and exist in suitable forms, that mining operations can concentrate it. REE-rich lunar minerals may contain REE abundances up to an order of magnitude greater than the urKREEP value, and several lunar lithologies contain demonstrably more REEs than Earth's bulk crustal reservoirs (Fig. 4). However, while the absolute abundances of REEs in some lunar minerals (e.g., apatite, merrillite, and monazite) are comparable to terrestrial ores, they are present only as trace phases and are therefore a volumetrically minor component of lunar rocks. Thus, based on current knowledge, lunar lithologies cannot yet be considered viable REE resources or targets for REE ore extraction.

6.2. Lunar U and Th distributions

Th and U are also incompatible in major lunar rock-forming minerals, with Th known to be closely associated with KREEP-rich lithologies in the PKT (e.g., Jolliff et al. 2000, Gillis et al. 2004). The highest spatial resolution images of lunar surface Th abundance are the 40–50 km/pixel maps produced by Lawrence et al. (2007, see their Figure 4) derived from spatial deconvolution of the Lunar Prospector gamma-ray data. These reveal maximum concentrations of ~17 ppm (essentially the same as the urKREEP value of 18 ppm; Warren and Wasson 1979) around the periphery of the PKT, and higher concentrations at smaller spatial scales cannot be excluded. The first map of lunar surface U concentrations was produced by the Gamma Ray Spectrometer on board the Kaguya spacecraft (Yamashita et al. 2010). Across the lunar surface, U concentrations
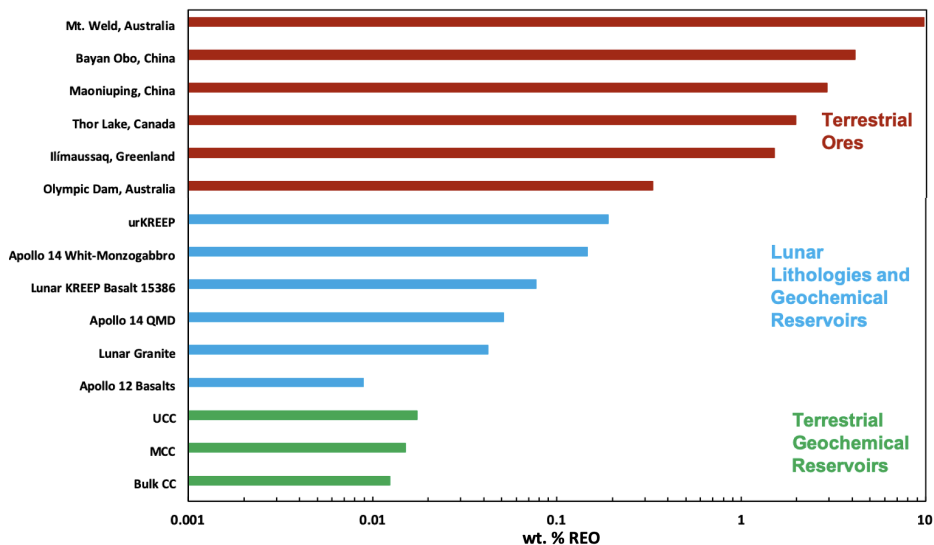
Figure 4. Comparison of REE abundances reported as wt. % oxides (REO) for bulk terrestrial crustal reservoirs (middle, upper, and bulk continental crust), bulk lunar lithologies, lunar ITE-bearing minerals, and terrestrial ore bodies. Data sources: Neal and Taylor (1989), Jolliff (1998); Neal and Kramer (2003); Rudnick and Gao (2003); Kartashov et al. (2006); Jolliff et al. (2006b); BGS (2011). Note the logarithmic scale.

average ~0.3 ppm (with maximum values up to ~2 ppm), and the average Th abundance was mapped at ~1.2 ppm. This yields an average Th/U ratio of ~4, consistent with bulk *in situ* samples (Korotev 1998) and the ratio expected for urKREEP (Warren and Wasson 1979).

As expected, the highest U concentrations are mostly located on the lunar nearside within the PKT with values up to 2.1 ppm. However, the spatial resolution of the Kaguya data (~130 km) is lower than the spatially deconvolved Lunar Prospector data (~50 km; Lawrence et al. 2007), and may mask locally higher concentrations. Adopting a Th/U ratio of 4 would imply maximum U concentrations of ~4 ppm in the regions of maximum Th abundance mapped by Lawrence et al. (2007). In addition to the PKT, smaller outcrops of Th-rich material occur elsewhere on Moon, most notably in the Compton-Belkovich region (Jolliff et al. 2011) and the north-west part of the South Pole-Aitken Basin on the farside. Wilson et al. (2015) identified a high-Th area approximately 75 km across at Compton–Belkovich with a Th concentration in the range 14±3 ppm, which would imply a U concentration of ~3.5 ppm.

Establishing the presence of U on the Moon has invited discussion of fueling nuclear power sources on the lunar surface, which might make long-term *in situ* operations on the Moon more sustainable. As discussed above, the highest lunar U abundances known to date are ~4 ppm, around the periphery of the PKT and in the region of Compton-Belkovich. This is higher than U concentrations of Earth's bulk crustal reservoirs, which range from 0.2 ppm in the bulk lower continental crust to 2.7 ppm in the upper continental crust (Rudnick and Gao 2003). However, 4 ppm is low compared to a concentration that would count as a U ore on Earth. A low-grade U ore body contains an average of 1000 ppm (0.1%) of U, where as a high-grade U ore body contains >20,000 ppm (>2%) of U (Ulmer-Scholle 2017). At present, therefore, no U-bearing regions on the lunar surface have been identified that would warrant their classification as an ore resource (although the technological and economic constraints on

the classification of mineral deposits as ore will be different on the Moon than on Earth, so a direct comparison may be misleading). Moreover, current lunar orbital surveys are restricted to studying surficial materials with relatively poor spatial resolution, so continuing exploration of the Moon may yet discover localities with economically exploitable U-bearing deposits.

7. LUNAR RESOURCES DERIVED FROM ASTEROIDAL AND METEORITIC SOURCES

The Moon has been bombarded by extra-lunar materials throughout its history, and it is reasonable to consider if any of the materials delivered to the lunar surface from outside may be useful as potential resources. In Section 3.4 we discussed the resource implications of solar wind-implanted volatiles (H, He, noble gases) and exogenous components (e.g., C, N, Fe) added to the regolith by micrometeorites. In this section, we address the possibility that some fraction of impacting asteroids and meteorites may survive impact with the surface, leading to localized enhanced concentrations of relatively unmodified extra-lunar materials.

Although small fragments of intact meteoritic materials have been found in the lunar regolith (see Joy et al. 2016 for a review), indicating that partial survival of some impacting bodies does occur, there is a general expectation that the bulk of such material will melt or vaporize on impact (e.g., Melosh 1989). On the other hand, numerical simulations of meteoritic and cometary impacts with the Moon indicate that significant projectile survival may occur if the impact is oblique and/or has a relatively low ($\leq$ 12 km/s) velocity (e.g., Pierazzo and Melosh 2000; Bland et al. 2008; Crawford et al. 2008; Yue et al. 2013; Svetsov and Shuvalov 2015). Projectile survival is also expected to depend on the shape and porosity of the projectile (Potter and Collins 2013).

Haskin et al. (1993) and Wingo (2004) have suggested that surviving remains of metallic asteroids (or the metallic cores of differentiated asteroids) would provide local enhancement in concentrations of Fe, Ni, Co, Cu, and the platinum group elements (PGEs). Given that these elements have typical concentrations in iron meteorites of ~85–90 wt%, ~5–10 wt%, ~0.5 wt%, ~100–300 ppm, and ~10–100 ppm, respectively (e.g., Kargel 1994; Mittlefehldt et al. 1998; Lodders and Fegley 1998), remnants of metallic impactors could be valuable sources of these materials. Although, the vast majority (>80%) of impacts on the lunar surface are likely to have an (ordinary) chondritic, rather than metallic, composition, even chondritic meteorites may contain sufficient metal to be valuable as a resource. For example, the H and L chondrites, which together comprise over 80% of chondritic meteorites, contain ~15–20 wt% and ~7–11 wt% metal, respectively (e.g., Jarosewich 1990; Hutchison 2004). Moreover, the remains of both metallic and chondritic meteorites are likely to be relatively easy to locate on the lunar surface owing to their magnetic signatures (Wieczorek et al. 2012).

Surviving material from carbonaceous projectiles could also prove to be valuable (e.g., Halim et al. 2021). If not too severely shocked during impact (which will depend on impact angle and velocity), these materials might contain water in surviving hydrated compounds (Svetsov and Shuvalov 2015; Halim et al. 2021). Moreover, even if the water is mostly lost during the impact, the surviving remains of carbonaceous projectiles may still contain C (several wt%), N (~0.1 wt%), and possibly intact organic molecules (e.g., Pierazzo and Chyba 1999; Matthewman et al. 2015) in concentrations much higher than found in most lunar materials. These would be useful for a range of *in situ* life support processes (including lunar agriculture), as well as possible industrial applications. However, identifying surviving remains of carbonaceous impactors will be more difficult than identifying metallic or chondritic remains because they will lack a magnetic signature.

Dark patches on the surface of Vesta have been interpreted as being due to carbonaceous impactors (e.g., McCord et al. 2012; Daly and Schultz 2016), but no such visible signatures have yet been identified on the Moon. While it is true that average impact velocities are expected to be higher on the Moon, survival of some fraction of carbonaceous impactors is nevertheless expected, especially for very oblique impacts (Halim et al. 2021). The lack of obvious surface markings may therefore be due to burial of the material and/or surface re-working. Developing remote-sensing and/or *in situ* techniques to identify bulk quantities of surviving carbonaceous material on, or just below, the lunar surface will be important for compiling an inventory of potential lunar resources.

We note that one advantage of the Moon as a source of asteroidal material is that many asteroids of differing compositions have impacted it throughout its history, giving rise to a correspondingly wide range of potential resources. There is an argument (e.g., Kargel 1994; Elvis 2012, 2014) that the most easily exploitable extraterrestrial sources for use in cis-lunar space, as well as for possible importation to Earth, will be near-Earth asteroids rather than the lunar surface. However, in the context of the future development of the Moon, where a surface infrastructure may be developed to support human operations for multiple purposes, access to surviving remnants of metallic, chondritic, and carbonaceous asteroids on the lunar surface may nevertheless prove to be economically valuable in this wider context also.

8. BULK REGOLITH AS A RESOURCE

The lunar surface is covered by a layer of unconsolidated regolith, the thickness of which varies from approximately 5 m on mare surfaces to about 10 m on highland surfaces (e.g., Carrier et al. 1991; McKay et al. 1991; Lucey et al. 2006; Plescia et al. 2023, this volume). The extreme lunar environment, and the processes that have acted on the regolith during its formation and subsequent exposure, give it unique compositional and mechanical properties. Understanding these properties will be essential in identifying potential uses for the lunar regolith, as well as for the safe transportation and handling of this material (e.g., Walton 2012; Just et al. 2020).

A great variety of potential uses for bulk regolith have been investigated over the years (e.g., Faierson and Logan 2012; Lim et al. 2017). These include berms and ridges for protection from rocket exhausts, radiation and micrometeorite shielding, and habitat thermal regulation. Indeed, on Earth one of the most important materials for construction is aggregate (i.e., the gravel and sand that are ubiquitous in modern infrastructure and construction), and it may come to play a similar role on the Moon. Though unaffected by the weathering processes prevalent on Earth, the lunar regolith has been disaggregated by meteorite impacts, thermal fragmentation, and space weathering into a form that is expected to be amenable to simple size separation techniques for producing basic manufacturing feedstocks. Suitably beneficiated, bulk regolith could be sintered or melted into building elements (e.g., blocks, bricks, columns, etc.), and on a larger scale into road and landing pad surfaces. The energy needed to drive such processes might be provided by concentrated sunlight, or through thermal energy via resistive or microwave heating.

Processing the regolith to produce building elements could be as simple as using excavators to move the material or trench it from the surface. Thus, simple, yet important, mission elements such as berms, trenches or rudimentary radiation shielding could be implemented. Advancing in complexity, packing regolith into sand bags ('Regolithbags') has also been investigated as a way to create building elements (Khalili 1989). At a somewhat higher level of complexity, sieved, but otherwise minimally processed, regolith might be thermally sintered to form a wide range of structural components (e.g., Desai et al. 1993; Indyk and Benaroya 2017; Woolf and Angel 2021). The sintering process allows lunar aggregate particles to bind together without completely melting, thereby consolidating and increasing the mechanical strength of the processed material (e.g., Meurisse et al. 2017). At higher temperatures the regolith might

be melted to form a range of glass products, including glass fibers for construction purposes (Ray et al. 2010) and mirrors for the concentration of sunlight (Schleppi et al. 2019).

One promising technique for processing lunar regolith involves microwave radiation (e.g., Taylor and Meek 2005; Srivastava et al. 2016; Lim et al. 2017; Lim and Anand 2019). The unique compositional properties of the regolith make it susceptible to coupling with microwaves, operating at the commonly used 2.45 GHz frequency. This can probably be attributed to the high concentration of iron minerals, including the presence of nanometer-sized Fe^0 grains within the agglutinate glass, although regolith simulants (which generally lack nanophase Fe) have also been observed to react in a similar manner to microwave radiation (Srivastava et al. 2016; Lim and Anand 2019). Compared to resistive heating, microwave irradiation may offer significant advantages, including rapid heating, faster melting, and lower overall energy requirements (e.g., Agrawal 2006; Sun et al. 2016). Microwaves may also be useful in the extraction of water from hydrated regoliths. Building blocks, roads and landing pads have all been envisaged as products of a rover-mounted microwave antenna (e.g., Srivastava et al. 2016).

Resistive heating and focused solar radiation are also readily applicable to the processing of lunar regolith (ESA 2017). There have been several demonstrations of the solar sintering approach (see, e.g., Meurisse et al. 2019, and the European Commission funded 'Regolight' project: http://regolight.eu/). Additive-driven approaches, such as lunar aggregate derived concrete ('lunarcrete') also utilise the bulk regolith (e.g., Lin 1985). Variations of this concept have recently been demonstrated with geopolymer and phosphate-based binders (Davis et al. 2017; Buchner et al. 2018).

With the widescale adoption of additive manufacturing (colloquially known as 3D printing), it is unsurprising that this fabrication approach has also been proposed as a use for bulk regolith material (for a review see Isachenkov et al. 2021). Indeed, the powder-like composition of the regolith makes it applicable as feedstock material for many 3D printing processes, and this methodology can allow for complex geometries to be realized. In 2013, ESA completed a study proposing a 3D printing process utilising regolith and a chlorine-based binder as a means of building structures for thermal, radiation and micrometeorite protection (Fig. 5; Cesaretti 2014). Additionally, ESA is now focusing on binder-free approaches, in an effort to reduce the amount of material that would need to be brought to the lunar surface.

Figure 5. A ~1.3 tonne building block produced as a demonstration of 3D printing techniques using lunar regolith simulant (Cesaretti et al. 2014); the overall length of the block is approximately 1.4 m. Image courtesy of ESA.

Contour crafting, an extrusion-based approach similar to the layer by layer technique commonly employed by conventional thermoplastic 3D printers, has been reported by Khoshnevis and Zhang (2012) where a sulfur-based concrete using regolith simulant was successfully printed. Recent work on forming structural components by 3D-printing of regolith simulants has been reported by Goulas et al. (2018), Taylor et al. (2018), and Meurisse et al. (2019).

9. THE LUNAR ENVIRONMENT AS A RESOURCE

Several aspects of the Moon's natural environment may also prove sufficiently useful to be classed as lunar resources (e.g., Burke 2012).

9.1. Quasi-permanent sunlight

As a result of the small inclination of the Moon's rotation axis with respect to the ecliptic (1.54°), illumination conditions at the lunar poles are extreme. Although it appears that nowhere on the lunar surface receives perpetual sunlight, areas that are illuminated for the majority of the time have now been identified at both poles (e.g., Fincannon 2008; Noda et al. 2008; Bussey et al. 2010; Mazarico et al. 2011; De Rosa et al. 2012; Speyerer and Robinson 2013; Gläser et al. 2014, 2018). LOLA-based illumination maps based on simulations over long time-periods (i.e., several 18.6-year lunar precession cycles) at 240 m/pixel and from the poles to ~75° latitude, reveal that total areas of 3.3 km^2 and 5.0 km^2 receive over 80% illumination in the vicinity of the north and south poles, respectively (Mazarico et al. 2011). Near the North Pole this area includes regions on the rim of Peary, Whipple and Aepinus craters. Near the South Pole the area includes portions of the rims of Shackleton and De Gerlache craters (and the connecting ridge between them), as well as the rim of Nobile crater and the crest of the Malapert Massif (Mazarico et al. 2011).

These locations are shown in Figure 3. Moreover, for most locations, a small height gain (2 to 10 m) can significantly increase the proportion of illuminated time, such that elevated solar arrays could provide a near-continuous source of power (Mazarico et al. 2011; Gläser et al. 2018). In addition to providing nearly continuous sources of electrical power derived from photovoltaic arrays, these locations will also be optimal sites for the location of direct solar thermal power systems such as those studied by Nakamura and Senior (2008).

9.2. Permanent shadowed regions as a resource

The importance of PSRs as traps for consumable volatiles, especially water, hydrogen and oxygen, was discussed in Section 3.1. Here, we note that the presence of water in PSRs open up additional possibilities for utilization, including energy storage in regenerative fuel cells (e.g., Bents et al. 2005; Fraser 2012). In these systems water is electrolyzed to produce hydrogen and oxygen gas during periods of energy surplus (e.g., during the lunar day), and recombined to produce water and electricity during the lunar night. The presence of well-illuminated regions close to PSRs in the lunar polar regions (Fig. 3) may make this form of energy storage especially attractive, and cryogenic storage of liquids and gases would be more efficient within PSR locations. Indeed, the extremely low temperatures within PSRs may prove useful for a range of industrial and scientific applications, including the cryogenic storage of volatiles and applications making use of high-temperature superconductors.

9.3. Vacuum as a resource

As noted by Schrunk et al. (2008), the fact that the vacuum of space extends to the lunar surface may be of value for a number of industrial processes, including vacuum vapour deposition, element concentration via ion sputtering, and the manufacture of ultra-pure materials. There are also clear scientific benefits of having easy access to vacuum at the lunar surface and these may influence the site(s) of future lunar operations. For example, the lunar surface is a potential

platform for a range of astronomical observations (e.g., Burns et al. 1990; Crawford et al. 2012; Silk 2018). In addition to requiring access to vacuum for their operation, astronomical instruments might also benefit from the vacuum deposition of metallic films to form the reflective surfaces for large liquid mirror telescopes (Borra et al. 2007; Angel et al. 2008) and the passive cooling of infrared telescopes during the lunar night or within PSRs (Lester 1992); the near-surface vacuum may also enable a range of fundamental physics experiments.

9.4. Lava tubes

Lava tubes form when a solid roof develops over molten lava which then drains away to leave a subterranean void (e.g., Greeley 1971). If accessible lava tubes exist on the Moon they could form a natural habitat providing protection from radiation, micrometeorites and the extreme temperature variation of the lunar diurnal cycle (Hörz 1985; Coombs and Hawke 1992; Haruyama et al. 2012). Conceivably, lunar lava tubes may prove to be a resource for trapping water and other volatiles. Scientifically, lunar lava tubes would also provide a thermally quiet, dust- and radiation-free environment to place scientific instruments (Haruyama et al. 2012), and the lava flow stratigraphy exposed in the tube walls and skylights may preserve a record of lunar volcanic history, solar activity, galactic cosmic rays, and dynamo magnetic field (e.g., Robinson et al. 2012; Crawford and Joy 2014). In addition, experience gained in living and working in lunar lava tubes would provide invaluable experience for later exploration of Martian lava tubes which are of potential astrobiological interest (Boston et al. 2001).

The search for lunar lava tubes initially concentrated on the observation of rilles (e.g., Coombs and Hawke 1992). Following the first discovery of a potential skylight in a sinuous rille in the Marius hills region (Haruyama et al. 2009), two further large (~100 m diameter) lunar pits were identified in Mare Tranquillitatis and Mare Ingenii (Haruyama et al. 2012). Higher resolution LRO images showed that these pits have overhangs and are potential lava tube skylights (Robinson et al. 2012; Wagner and Robinson 2014). The existence of large subsurface voids several 10s of km in length, and possibly ~1 km in width, near these skylights have been indicated by gravity anomalies measured by the GRAIL spacecraft (Chappaz et al. 2017) and the SELENE Lunar Radar Sounder (Kaku et al. 2017). Calculations, based on the composition of lunar basalt and the low gravity, have shown that lunar lava tubes >1 km across might exist (Blair et al. 2017), compared to the ~30 m maximum diameter terrestrial lava tubes.

To date, over 200 lunar pits have been identified (Wagner and Robinson 2014), with the majority found in impact melt deposits. These may be formed by the impact melt forming a hard skin followed by the impact melt draining away, with later meteorite impacts puncturing the skin (Martellato et al. 2013). Thus, in addition to lava tubes, impact melt pits potentially offer a geographically wide range of protected environments for human activities on the Moon.

9.5. Mini-magnetospheres

The Moon has no global dipolar magnetic field to protect its surface from the solar wind, solar energetic particles (SEP), and galactic cosmic rays (GCR), but locally strong crustal magnetic anomalies on the scale of hundreds of kilometers do exist (e.g., Hood et al. 2001; Mitchell et al. 2008; Tsunakawa et al. 2010). Mini-magnetospheres, or partial voids in the solar wind, have been identified in association with some magnetic anomalies (e.g., Kurata et al. 2005; Halekas et al. 2008; Wieser et al. 2010; Yokota et al. 2014), demonstrating that these local magnetic anomalies can deflect the relatively low-energy particles of the solar wind. Many magnetic anomalies are also associated with albedo anomalies known as lunar swirls (e.g., Schultz and Srnka 1980; Blewett et al. 2011; Denevi et al. 2016). Spectral reflectance observations of bright lunar swirls reveal evidence for reduced space weathering (e.g., Kramer et al. 2011; Glotch et al. 2015) as well as depleted FeO and OH abundances (Blewett et al. 2011; Kramer et al. 2011), while "dark lanes" associated with swirls appear to have experienced enhanced space weathering and the production of larger (>40 nm) nanophase

iron particles (e.g., Kramer et al. 2011). It has also been suggested that off-swirl regolith may become saturated with hydrogen at higher levels than normal lunar soil due to the presence of a magnetic field, with implications for the production and resource potential of OH or H_2O (Zeller et al. 1966; Morris 1976). Further efforts are needed to assess the effects of magnetic fields on the production or retention of potential resources such as metallic Fe, H, OH, and H_2O in these regions of the Moon (e.g., Hood 1992).

Many of the observed properties of lunar swirls have been successfully reproduced by models which show the formation of a narrow electrostatic field as a result of the solar wind plasma impacting the plasma formed around the fixed surface magnetic anomaly (Bamford et al. 2016). The importance of these electric fields in deflecting high-energy particles during SEP events has been demonstrated in studies of artificial mini-magnetospheres (e.g., Adams et al. 2005; Bamford et al. 2014), however further study is required to determine whether the natural lunar mini-magnetospheres are strong enough to deflect energetic particles and provide effective shielding for human explorers.

10. NEXT STEPS IN LUNAR RESOURCE CHARACTERIZATION

The next phase for developing lunar resources will involve a number of exploration steps that will also have significant scientific value. Any discussion of lunar resource potential must recognize that our understanding of the Moon's geology is still very incomplete. Current ground-truth is based on the study of samples returned from just ten localities (all on the nearside at sites that are not ideal for ISRU), lunar meteorites of generally unknown provenance, and on the interpretation of orbital remote-sensing data which only probe the uppermost few meters (and often only the uppermost few microns) of the lunar surface. It follows that, to properly assess the extent to which the Moon may host economically useful materials, an extensive future program of exploration will be required (Carpenter et al. 2016).

10.1. Distinguishing between resources and reserves

In considering the utilization of lunar materials, it will be helpful to distinguish between a 'resource' and a 'reserve'. In terrestrial mining terms, a 'mineral resource' is defined as:

- A concentration of naturally occurring solid, liquid, or gaseous materials in or on the Earth's crust in such form that economic extraction of a commodity is regarded as feasible, either currently or at some future time (USGS 2010).

- A concentration or occurrence of solid material of economic interest in or on the crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction (CIM 2014).

Whereas a 'mineral reserve' is defined as:

- That portion of an identified mineral resource from which a usable mineral or energy commodity can be economically and legally extracted at the time of determination (USGS 2010).

- The economically mineable part of a mineral resource (CIM 2014).

Given these definitions, and the orbital and sample data available, it seems clear that potential resources do exist at or close to the lunar surface, but further exploratory activity is required to determine if they constitute useable reserves. The requirements and objectives for such a program are elaborated below.

10.2. Orbital remote sensing

Multiple aspects of lunar resource characterisation would benefit from improved spatial resolution in orbital remote sensing data. Key examples include:

10.2.1. Neutron spectroscopy. Confirmation of the presence of water ice and other volatiles in lunar PSRs, and assessment of the total polar water inventory, is one of the highest priorities in lunar resource prospecting. Such information may be obtained by neutron spectroscopy with a resolution of ≤ 10 km so that correspondence between water-rich areas and individual PSRs, and the possible extent of near-sub-surface ice outside of PSRs, may be determined (Section 3.1; see also discussion by Mitrofanov et al. 2010; Lawrence 2017). Based on the LCROSS impact results, Colaprete et al. (2010) noted that the distribution of water ice in and around PSRs may vary on scales smaller than 10 km, so higher resolution neutron mapping would be desirable.

10.2.2. X-ray fluorescence spectroscopy. X-ray fluorescence (XRF) spectroscopy is a powerful technique for determining the abundances of major elements (e.g., Na, Mg, Al, Si, K, Ca, Ti and Fe) on atmosphere-less planetary surfaces (e.g., Yin et al. 1993). Its main limitations are that XRF only occurs in the uppermost few microns of the surface material, and that implementations to-date have had a relatively low spatial resolution (typically 10s of km; e.g., Crawford et al. 2009; Narendranath et al. 2014). However, XRF instruments with spatial resolutions on the order of a few km are under consideration for both the Moon and Mercury (e.g., Fraser et al. 2010; Hong et al. 2017), and the technique is in principle able to probe sub-surface compositions by analyzing the compositions of the ejecta from craters of a range of sizes (Crawford et al. 2009). The main value of orbital XRF measurements for resource prospecting will probably be in the identification of outcrops of evolved lithologies through enhanced concentrations of elements such as Na and K, and where enhanced concentrations of U, Th and the REEs may occur (Section 6). It could also be useful in identifying locations where remnants of asteroidal impactors may occur close to the surface (Section 7).

10.2.3. Infrared spectroscopy. Whereas XRF spectroscopy is sensitive to individual chemical elements, NIR spectroscopy is sensitive mainly to the mineralogical composition of a planetary surface. It has already proved to be a powerful technique for identifying potential lunar resources, especially as implemented by the M^3 instrument on Chandrayaan-1 with the detection of hydrated regolith at high lunar latitudes (Section 3.2) and hydrated pyroclastic deposits (Section 3.3). Global M^3 data have a spatial resolution of ~140–280 m/pixel (depending on the spacecraft orbit), and targeted observations have a resolution of ~70 m (Pieters et al. 2009b). It is not clear that higher spatial resolution is required for resource prospecting purposes. However, as the number of M^3 targeted observations was quite limited, there may be a case for a dedicated orbital NIR spectrometer having a spatial resolution of a few tens of metres. In addition, it would be desirable if the wavelength range of NIR spectrometers could be extended beyond 3 μm (ideally to at least 3.6 μm), to properly capture the profiles of bands of OH and H_2O-ice in that spectral region. Prospecting applications that would benefit from such an instrument include locating areas with above average concentrations of hydrated materials (Sections 3.2 and 3.3), and searches for surviving remnants of carbonaceous impactors on the lunar surface (Section 7). An example of such an instrument is the High-resolution Volatiles and Minerals Moon Mapper (HVM^3), recently proposed for NASA's Lunar Trailblazer small satellite lunar orbital mission (Thompson et al. 2020).

10.2.4. Thermal infrared (TIR) mapping. Observations in the thermal infrared will be important for the characterization of lunar thermal environments. PSRs and adjacent areas where volatiles are stable in the near subsurface can exist on meter-scales, far below the resolution of current temperature data products from Diviner (~240 m). These abundant, smaller cold traps may be considerably easier to access for prospecting and resource extraction.

Therefore, there may be a case for a higher spatial resolution TIR instrument capable of bridging the gap between large-scale and small-scale cold traps. An example of this kind of instrument is the Lunar Thermal Mapper, also proposed for the Lunar Trailblazer mission (Bowles et al. 2020).

10.3. *In situ* surface measurements

Although there is some scope for continued prospecting from orbit, there is now a pressing need for surface measurements, both to ground-truth remote-sensing measurements and to probe smaller spatial scales than is achievable with orbital remote-sensing instruments. It is also important to obtain information on the sub-surface distribution of potential resources. Several possibilities exist for obtaining such measurements.

10.3.1. Hard landers/penetrators. Expendable probes, such as LCROSS (Schultz et al. 2010) and the Moon Impact Probe carried by Chandrayaan-1 (Kumar et al. 2009), have demonstrated the value of surface measurements. To date, the LCROSS mission has provided the only ground-truth measurement for lunar water ice, at a single point within a single PSR (Section 3.1; Colaprete et al. 2010), and additional measurements are urgently required to establish if water ice deposits within PSRs constitute useable reserves. Hard landers and penetrators appear particularly well-suited to making such measurements, especially as many PSRs are surrounded by steep slopes (e.g., Smith et al. 2017) making them difficult to access using rovers. Instrumented penetrators, designed to make scientific measurements during and after impact (e.g., Smith et al. 2009), could address several major questions of resource availability by measuring the mechanical and thermal properties of the upper few metres of regolith, performing *in situ* mass spectrometry for water ice and volatile content, and obtaining imagery for geological context (Barber et al. 2018). The deployment of multiple, expendable low-mass (~0.1 kg) 'nano-landers' is another potential means of gathering relevant information on thermal and geotechnical properties within PSRs (e.g., Crites et al. 2019; Riu et al. 2020).

10.3.2. Static landers. Although more expensive to implement, robotic soft landers are able to carry more sophisticated instruments than can hard landers or penetrators. After a long hiatus, soft landings on the Moon resumed with the Chang'e-3, 4 and 5 missions between 2013 and 2020, and multiple international surface landers are currently planned, including commercial US missions funded through the Commercial Lunar Payload Services (CLPS) program (https://www.nasa.gov/content/commercial-lunar-payload-services). Of particular interest from a lunar resources perspective is ESA's PROSPECT payload (Carpenter et al. 2016; Barber et al. 2017). This is intended to land at a high southern (but non-PSR) latitude where hydrated surface materials are thought to exist (Section 3.2) and deploy a drill to determine the composition of the uppermost meter of regolith, thereby constraining the vertical extent of hydrated materials. It is also proposed to carry an active ISRU experiment, in the form of an oxide-reduction demonstration (Barber et al. 2017; Sargeant et al. 2020). Lunar resource prospecting would clearly benefit from additional missions along these lines, both at the poles and in regions where resources other than water may occur close to the surface. Examples include pyroclastic deposits (Section 3.3), areas where geological processes may have concentrated valuable materials (e.g., Sections 5 and 6), and areas where the surviving remnants of asteroidal impactors are suspected (Section 7).

10.3.3. Rovers. Rover-enabled mobility will greatly enhance both the scientific and resource-prospecting value of lunar landers. Mobility in and around PSRs will be especially valuable for characterizing the distribution and physical state of water and hydrated materials at the lunar poles (e.g., Elphic et al. 2015; Heldmann et al. 2015), although rovers operating within PSRs would need to be able to survive total darkness and cryogenic temperatures for long periods of time which poses significant engineering challenges. Much valuable development work was performed in the context of NASA's (now cancelled) Resource Prospector (RP) rover and associated payload (Sanders and Larson 2015; Colaprete et al. 2017), and this has fed into

the design of the Volatiles Investigating Polar Exploration Rover (VIPER) which should land in the lunar south polar region in 2023 as part of the CLPS program (Colaprete et al. 2020). However, a full characterization of lunar PSRs will require many robotic rovers, and supplementing rover-borne instruments with cheaper instrumented penetrators deployed from orbit (Section 10.3.1) may be an attractive strategy. As noted above in the context of static landers, prospecting for potential resources in addition to water (e.g., pyroclastic deposits, outcrops of evolved lithologies, and asteroid impact sites) would also benefit from rover-enabled mobility, and where the environment will be more benign than for PSRs.

10.3.4. Hoppers. Some of the advantages of static landers on the one hand, and highly mobile rovers on the other, might be combined if the former were able to 'hop' between multiple locations (e.g., Mège et al. 2016). Such concepts have not yet been implemented, but appear worth further consideration for both scientific exploration and resource prospecting.

10.4. Synergies with human exploration

Strong scientific reasons exist for returning human explorers to the lunar surface (e.g., Spudis 1996; Crawford et al. 2012; Neal et al. 2014). Many of these scientific objectives would be best served by the creation of one or more scientific research stations, perhaps on the model of existing research stations in Antarctica (e.g., Taylor 1985; Ehrenfreund et al. 2012; McKay 2013). It seems clear that the scale and affordability of lunar bases will be enhanced if they are able to utilize local resources, especially local sources of water, oxygen, and building materials (e.g., Duke et al. 2006; Schrunk et al. 2008; Benaroya 2010; Anand et al. 2012; Spudis 2016). It is also true that the scientific and technical infrastructure provided by an outpost of this kind will greatly aid in the utilization of lunar resources and in the prospecting for additional resources. In addition, a lunar outpost could help kick-start a space economy by providing a market for commercial space resource companies while at the same time providing infrastructure to support their activities (e.g., Spudis and Lavoie 2011; Crawford 2016; Metzger 2016; Sowers 2016; Kornuta et al. 2019). For these reasons, strong synergies exist between human missions to the Moon and the utilization of lunar resources that need to be taken into account in the development of future human exploration initiatives (e.g., Neal et al. 2014).

11. THE INTERNATIONAL AND LEGAL CONTEXT

Lunar resources, and space resources more generally, have the potential to open the Solar System to a wide range of human activity, including science, industry, commerce, tourism and, perhaps eventually a permanent human presence. As this potential becomes increasingly recognized, many different actors, including both new space-faring nations and private companies, are actively developing interests in prospecting for, and eventually utilizing, space resources. As this activity moves towards implementation, however, it will become increasingly important that it is managed, or at least coordinated, to avoid duplication of effort, mutual interference, or possible conflict.

A positive start was made with respect to international cooperation in 2007 when fourteen of the world's space agencies agreed on the *Global Exploration Strategy: The Framework for Coordination* (GER 2007), which resulted in the formation of the International Space Exploration Coordination Group (ISECG; http://www.globalspaceexploration.org). Among the first fruits of the ISECG was the formulation of the Global Exploration Roadmap (GER), which outlines an international collaborative framework for the robotic and human exploration of the Solar System, focusing on destinations where humans may one day live and work (ISECG 2017). International coordination of space resource utilization, at least at the space agency level, may therefore be achieved through ISECG and the GER. That said, ambiguities remain regarding the legal status of space resource utilization, especially regarding the strategic interests of nation-states above the space agency level, and the rights and obligations of private commercial companies.

The dangers of interference between different nations and/or commercial entities utilizing lunar resources will become apparent if we consider that some potential resources (e.g., well-lit polar localities, concentrations of water ice, entrances to lava tubes, and the remains of metallic or carbonaceous asteroids) may occupy very restricted geographical areas (e.g., Elvis et al. 2021), where only one operator could plausibly operate at a given time. Elvis et al. (2016) have highlighted the particular case of the handful of desirable well-lit polar localities, each having a surface area of at most a few square kilometres (and some considerably less) which, in the absence of any coordinating principles, may effectively end up being appropriated on a first-come-first-served basis. Even if such an outcome is consistent with international law, which is debatable (e.g., Tronchetti 2009, 2016; Pop 2012; Viikari 2012; Hao and Tronchetti 2017), it may not be in the long-term interests of the efficient utilization of the resource.

The over-arching legal framework governing space activities is based on the 1967 'Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies', more commonly known as the Outer Space Treaty (OST). The OST currently has 110 States Parties, including all nation-states having a spacefaring capability, and it establishes some important principles. These include the concept that space activities should be considered 'the province of all mankind' (Article I), that outer space is free for the 'exploration and use' by all states (Article I), that the Moon (and other celestial bodies) cannot be 'appropriated' by nation-states (Article II), and that existing international law holds in outer space (Article III). The OST has proved to be an excellent foundation for international space law but, being a product of its time, it makes no explicit reference to the utilisation of space resources, or to other commercial space activities not envisaged in 1967.

It is important that the current legal ambiguity regarding lunar resource utilization be clarified for at least three reasons: (i) commercial operators will need to be sure that they will have legal entitlement to any resources they extract if they are to invest in lunar resource utilization; (ii) operators acting under different national jurisdictions will need to know which regulations apply if they come into contact with each other; and (iii) locations on the lunar surface determined to be of exceptional scientific importance or historical interest (e.g., the Apollo landing sites) may need legal protection from resource extraction activities if scientific investigations or cultural heritage are not to be compromised.

In the absence of a new international treaty clarifying these issues some nation-states are considering, and in the case of the United States and Luxembourg have already enacted, their own national legislation governing space resource utilisation. This legislation (US Congress 2015; Luxembourg Chamber of Deputies 2017) is aimed primarily at providing reassurance to commercial operators that, at least within their own national jurisdictions, they will have legal title to the products of their space resource activities. This is intended to encourage commercial investment, and therefore addresses the first of the requirements identified above. However, these national legal frameworks are still reliant on the OST when it comes to the international context, and, if other nation-states follow the examples of the United States and Luxembourg, there is a danger that differing interpretations of the OST within different national jurisdictions could lead to confusion (e.g., Tronchetti 2016; Hao and Tronchetti 2017). Moreover, neither of the two national laws enacted to-date provides for the protection of sites of scientific or historical interest. The US-led Artemis Accords (https://www.nasa.gov/specials/artemis-accords/index.html) are a recent attempt at international coordination, but only a subset of space-faring nations are signatories. For these reasons, further development of the international legal framework governing the use of space resources, both on the Moon and elsewhere in the Solar System, appears warranted (e.g., Lefeber 2016; Bittencourt Neto et al. 2020). A comprehensive summary of the international lunar legal landscape has recently been provided by Masson-Zwann and Sundahl (2021).

12. SUMMARY

The Moon possesses abundant raw materials that are of potential economic value for future human activities in space, beginning with the use of lunar materials to facilitate human activities on the Moon itself (including scientific exploration, resource prospecting, and, perhaps, tourism) and progressing to the use of lunar resources to underpin a growing industrial capability in cis-lunar space. In this way, gradually increasing access to lunar resources may help 'bootstrap' a space-based economy (e.g., Wingo 2004; Spudis and Lavoie 2011; Metzger et al. 2013; Sowers 2016; Kornuta et al. 2019). That said, it is important to reiterate that our knowledge of lunar geological evolution, and the extent to which the Moon may offer economically useful resources, is still very incomplete. Gaining a more complete picture of the Moon's economic potential will require a much more ambitious program of lunar exploration than has been conducted to-date, and this will ultimately require the return of human explorers to the lunar surface. Indeed, clear synergies exist between human lunar exploration and the identification and utilization of lunar resources: lunar resources will help facilitate exploration, while exploration will help identify lunar resources.

It is important to acknowledge that the Moon is not the only source of extraterrestrial raw materials, and near-Earth asteroids (NEAs) are often discussed in this context (e.g., Kargel 1994; Elvis 2012). However, the Moon is likely to remain of central importance because of its constant proximity to Earth, its probable concentrations of accessible volatiles (especially water ice at the poles), and the fact that diverse lunar geological processes have concentrated several economically important materials (e.g., Ti, Al, the REEs, and U) to levels in excess of those found in known classes of NEA. Additionally, although it has long been considered that NEAs would be the preferred extraterrestrial sources for iron, nickel and the platinum-group elements, the possibility that the lunar surface may retain partially intact metallic meteorites (e.g., Wingo 2004; Wieczorek et al. 2012) implies that the Moon may become a useful source for these materials also. Last, but not least, the lunar surface lends itself to supporting a diverse scientific and industrial infrastructure in a way that asteroid surfaces do not. For all these reasons, it seems likely that the Moon and its resources will prove to be the linchpin in humanity's exploration and utilization of the Solar System.

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