the Cascadia subduction trench and onshore, mantle flow aligns with the subduction direction. Together, these observations are consistent with the idea that asthenospheric mantle below the Juan de Fuca Plate flows in line with plate motion.

However, the researchers find that mantle flow beneath the smaller, slow-moving Gorda Plate exhibits a very different pattern of anisotropy, even though it is just as young as the Juan de Fuca Plate. Here, the inferred mantle flow direction is not parallel to the direction of plate motion. Instead, seismic anisotropy aligns with the northwesterly direction of motion of the adjacent Pacific Plate. Using a simplified numerical model, Martin-Short and colleagues show that the rapid motion of about 6 cm per year of the large Pacific Plate can entrain mantle within a layer roughly 100 km thick below the Gorda Plate. This means that movement of the Gorda Plate is decoupled from the asthenosphere, perhaps because the plate is so small and slow moving.

The offshore measurements presented by Martin-Short and colleagues[2] also reveal northwesterly mantle flow at the southern end of the Cascadia subduction zone, which is interpreted to be induced by the Pacific Plate. Yet, previous onshore measurements were interpreted as southeasterly mantle flow around the edge of the subducted Gorda Plate[8]. Discriminating between these competing interpretations at Cascadia will require geodynamic models that incorporate the effects of mantle entrainment by plate motions and subduction-induced flow. In addition, more work is needed to quantify how the age, size and speed of an oceanic plate affect its coupling to the underlying mantle. A recent global study[9] suggests that coupling is strongest for plates that are moving at more than 4 cm per year. At Cascadia, the Juan de Fuca and Gorda plates are both relatively slow-moving, yet only the mantle below the Juan de Fuca Plate seems to flow in the direction of plate motion. The measurements by Martin-Short and colleagues indicate that plate size may also be a key factor that controls coupling. Geodynamic models, as well as observations of anisotropy over other small oceanic plates, are needed to resolve these questions.

Martin-Short *et al.*[2] provide a high-resolution view of mantle deformation over an entire tectonic plate system, from mid-oceanic ridge to subduction zone. They demonstrate that mantle deformation cannot simply be inferred from present-day plate motions. ❒

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PLANETARY SCIENCE

Cooking up the Moon in two steps

Compared to Earth, the Moon is depleted in volatile species like water, sodium and potassium. Simulations suggest that much of the Moon formed from hot, volatile-poor melt in a disk of debris after initially amassing cooler, volatile-rich melt.

Steve Desch

The Moon has long been associated with food, from a wheel of cheese to a big pizza pie. But the recipe for how the Moon was made remains an active debate. Most theorists agree that the ingredients include a proto-Earth and another, now-obliterated planet. The basic recipe is as follows: first, smash together the two planets to produce an Earth, orbited by a protolunar disk of melted and vaporized rock from both bodies. Second, stir the debris until the melt jells into thousands of moonlets. Third, collect the moonlets into a Moon and discard the scraps, either into space or onto Earth. This procedure makes an Earth and Moon much like our own. Beyond this basic recipe, would-be lunar cooks experiment and wrangle over how fast to spin out the disk, and how hot and for how long to bake the moonlets. No model yet has quite captured the Moon's exact flavour, including its abundances of volatile elements like sodium and potassium.

Writing in *Nature Geoscience*, Canup *et al.*[1] simulate the thermochemical evolution of the protolunar disk and quantify its volatile abundances. Using a two-step recipe, they match the Moon's volatile depletions and interestingly predict a lunar interior that is more volatile-rich.

The volatility of elements is defined by how easily they are lost by evaporation from a melt. Volatile elements such as Sb, Bi, Zn, Cd, Br and Tl readily evaporate at relatively low temperatures. Analyses of lunar samples suggest that volatile elements are depleted by factors of about 100 in the lunar interior compared to the Earth's mantle[2]. Hydrogen in the form of water seems to be similarly depleted in most lunar samples[3]. On the other hand, refractory elements like Sr, Ba, Be, Eu and Mg that evaporate at high temperatures are present in the Moon in the same proportions as in the Earth's mantle. The moderately volatile elements Na, K, Rb and Cs are only slightly depleted — Na and K are both depleted, relative to Earth's mantle, by factors of about 5 (ref. 2).

Quantitatively explaining these depletion patterns has presented a challenge. If the Moon formed from a disk of melted and vaporized rock, one might naively expect it to contain no volatiles at all. However, Earth's gravity effectively inhibits the escape of vapour from the disk[4]. So why shouldn't the Moon have the same volatile abundances as Earth?

The new model from Canup *et al.*[1] explains these depletions. Based on previous simulations of the Moon-forming impact, they assume an initial Earth-orbiting protolunar disk that extends from one to five Earth radii and consists of a two-phase mixture of about 80% melt and 20% vapour. According to previous models of the thermal evolution of the disk[5,6], the outer disk cools quickly and most of its vapour condenses

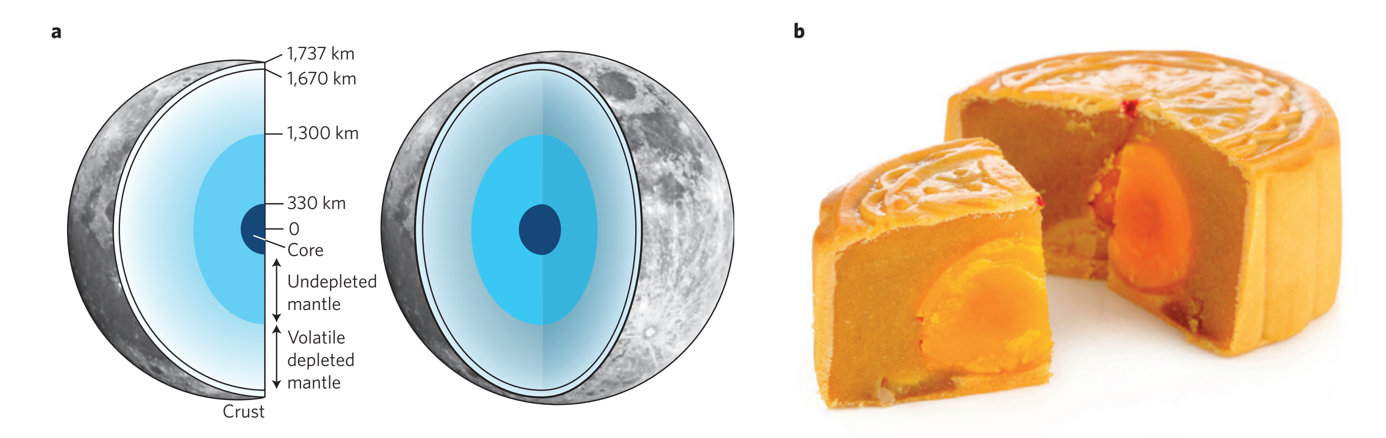

Figure 1 | Making the Moon from a two-step recipe. **a**, Model simulations by Canup *et al.*[1] suggest that the Moon's deep interior has Earth-like abundances of volatile elements, whereas the outer half of the Moon is relatively volatile-poor. **b**, A traditional Chinese mooncake also has a dry exterior and more volatile-rich interior, although the formative processes are not analogous.

into melt particles. Outside the Roche limit at 2.9 Earth radii — the distance at which a moonlet's self-gravity can resist being torn apart by the Earth's tidal forces — melt coalesces into moonlets in a matter of months. These dynamical simulations track the fate of the moonlets as they accrete to form the Moon and show that in the first few months after the impact, 40% or more of the Moon forms in the rapidly cooling disk beyond the Roche limit, from relatively cold material.

Inside the Roche limit, however, tidal shearing stresses rip apart any moonlets that form and heat the disk such that vapour persists for over 100 years[5,6]. The hot inner disk material spreads beyond the Roche limit over the next hundred or so years and spawns a second batch of moonlets. Initially, these too are added to the growing Moon, but as the Moon's orbit gradually spirals away from the disk the remaining moonlets are instead eventually added to Earth. Interestingly, Canup *et al.*[1] find that the second batch of moonlets forms from material that is initially still too hot for much of the vapour phase to condense. This suggests that this second batch of moonlets is formed from material that is volatile-poor.

Canup *et al.* combine these state-of-the-art dynamical and thermal models[5,6] with a chemical model to determine the composition of the moonlets and that of the growing Moon. The result is a single, comprehensive model that successfully reproduces the volatile element abundances in the Moon. Canup *et al.* find that while the final 60% or so of the Moon is growing, the inner disk remains hotter than the condensation temperatures of the moderately volatile elements sodium and potassium. Thus at least 60% of the Moon's mass is made of volatile-depleted moonlets spawned from the inner disk. The remaining volatile elements in the disk would condense after lunar accretion had ceased, and instead be added to the Earth.

No other model of the Moon's formation is as comprehensive, or is as capable of making such detailed predictions about the Moon's composition. The model used by Canup *et al.* shows depletion in Na and K of similar magnitudes as observed in lunar samples. Furthermore, their model suggests that the Moon's exterior is dry and volatile-depleted, but that its inner portions possess similar volatile abundances to the Earth's mantle (assuming no widespread mixing in the lunar interior after formation). This is consistent with measurements of pyroclastic glasses, thought to be sourced from the deep lunar interior, that show water abundances similar to those of the Earth's mantle[7,8]. Determination of the abundances of other volatile elements at shallow and deep levels in the lunar interior will further test this model.

One issue not addressed by Canup *et al.* is the enigmatic isotopic similarity of the Moon to the Earth for most refractory elements analysed thus far. The impacting planet is thought to have contributed disproportionately to the protolunar disk, so it is odd that the Moon should so closely resemble Earth in its isotopic composition. One proposed solution is that the proto-Earth and impactor were more isotopically similar than other planetary bodies in the inner solar system[9]. That begs the question of why isotopic ratios of volatile elements like zinc differ between the Earth and Moon[10]. This may be explained in the framework put forth by Canup *et al.*[1] if isotopic fractionations arise as elements condense out of the vapour phase and dissolve in the melt. Experimental verification is needed to test whether such isotopic fractionation of volatile elements under disk conditions matches observations.

Canup *et al.*[1] have developed a model that successfully reproduces the overall pattern of volatile depletions in the Moon. In the model (Fig. 1), the deep lunar interior forms in the months to years following the Moon-forming impact from material rich in water and volatiles. This is followed in later decades by the addition of volatile-poor material, such that the outer half of the Moon is depleted in volatile elements. The resulting volatile dichotomy predicted for the Moon loosely resembles *yue bing*, the 'mooncakes' that are served at a Chinese festival celebrated each autumn. In a mooncake, a moist filling — often lotus seed paste and salted duck egg yolk — is made first, and then baked inside a relatively dry pastry. The ingredients for the Moon are rather different and rather less tasty. But, like the making of *yue bing*, cooking up the Moon may require a two-step recipe. ❐

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