

12. Research topics

What the model opens for other researchers

Parts A--K · 118 topics · three lists for choosing

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The prose is written to be read by a general readership.

Abstract

The LEF model (Lunar Elevation and Fission) proposes that the Moon was built from the Earth's own material while it was still attached to the Earth. A fast-spinning, hot Earth raised a pear-shaped extension of its own material; deep, volatile-rich melt was fed up through it into a body on its tip; the Earth's outer shell over the region rose with that body as the surface of a dome and became its crust; and the body was released when its centre of mass reached the corotation line, the distance at which a body turning with the Earth already moves at orbital speed. Papers 1-11 of the series set out this process, its orbit, the maria, the craters, the poles, South Pole-Aitken, the stripes of the Pacific floor, the moons of Mars, and the requirements the Moon must meet.

This paper is a companion to the series. It computes nothing new. It collects, from all eleven papers, what the series has left open: requirements not yet tested, studies defined but not yet run, calculations the papers mark "to be computed", and the rows that the summary of Paper 1 marks as partial or awaiting. To these are added fifteen questions from the working notes of the series, nine of them the author's own proposals, that the papers have not yet taken up. Each such item is stated as a research topic that another group can take up as a paper of its own. Items that recur in several papers are merged into one topic, with every source kept.

There are 118 topics, grouped by theme in ten parts (A-J): the Earth before and during the pear; the body on the tip; the orbit; the maria and the openings; the craters and their source; the poles; South Pole-Aitken; the stripes and the Pacific; Mars and other bodies; and the requirements and key tests. Each topic is given with its question in one sentence, what the model predicts (with the number from the series), the data that exist or are needed, the method, and where in the series it is treated. Part K gives three lists for choosing: the two key observations of the model, the topics that can be done now on public data, and those that need a large simulation, a mission or samples.

WHAT THIS PAPER PROPOSES

The model is stated; its calibration is work for many hands. Papers 1–11 present one process, from a hot, fast-spinning Earth to a Moon on its present orbit, and test it against the Moon, the Earth and Mars. Along the way each paper fixed what the process requires and left some numbers to be computed with tools larger than one author's: three-dimensional simulations, equations of state at 50–150 GPa, coupled thermal-orbital integrations, laboratory work, missions and samples. We propose that these are not gaps in the model but the next stage of it. Each requirement is a topic for a paper by another researcher; the model sets the question and states the number it expects. The requirements of the model, and what would test it, are collected in Paper 11 (The Requirements).

118 topics, each with its own test. Every topic names the observation or calculation that decides it. Most are calibration: they will sharpen a number the series gives as a range (the expansion of the hot parent, the time of failure of the contact, the dissipation history of the Earth). Some are confirmations of a prediction already partly met (the order of sealing of the maria, the young craters of the poles, the Pacific low-velocity province). Two are the key observations of the model: *the geometry of the exposure zones* — whether the crust and the crater record are ordered in three concentric zones about the near-side centre (topics 107–108) — and *the source of the craters* — whether the material that made them is returned terrestrial material, as the model requires, or foreign material from outside the Earth-Moon system (topics 49 and 109).

What this paper does not do. It does not recompute any result, change any number of the series, or weaken any claim. The numbers quoted are those of the papers, with the paper and section given, so that a reader can go to the full derivation. Two subjects named by the series as future work — the Earth-Moon axes system and the Moon's magnetism — are mentioned once at the end and are not numbered among the topics.

Introduction — how to use this paper

The papers of the series tell one process in order. Each of them, in its last parts, collects what it requires, how it is tested, and what it leaves to further work. Read one after another, these lists are scattered across eleven papers and several hundred pages. This paper gathers them into one place and states each item so that a researcher outside the series can begin from it without first reading the whole series.

What a topic is. A *research topic*, here, is one open question of the model that can be the subject of a paper of its own. It comes from one of five places: a requirement that has been stated but not yet tested (the requirements R1–R18 of Paper 11); a study that a paper defined, with its thresholds fixed in advance, but did not run; a calculation that a paper marks as still to be made; and a row of the summary table of Paper 1 (§D.1), which marks each claim of the series as shown, partial or awaiting — in the colours of a traffic light, green, orange and red; and a question raised in the working notes of the series, with the model's expected answer, but that no paper has yet taken up (fifteen topics, at the end of Parts B, D, E, G, I and J). Where the same question appears in several papers, it is given once here, with all its sources.

How a topic is presented. Each topic opens with a short paragraph in plain words: what the question is about, and why it matters to the model. Five tagged lines follow. *The question* states it in one sentence. *What the model predicts* gives the number or the direction the series expects, with the paper in which it appears. *Data* says what exists or what is needed. *Method* names the tool. *Where in the series* points to the paper and section (“Paper 3 §C.5”), so that the full derivation can be found. The numbers are the series’ numbers; none is recomputed in this paper.

How the topics are grouped. Parts A-J follow the process of the model and then its tests: the Earth before and during the pear, the body on its tip, the orbit after release, the maria, the craters, the poles, South Pole-Aitken, the Pacific floor, Mars and other bodies, and finally the requirements and key tests. The table below gives the parts with their topics.

Part	Theme	Topics	Numbers
A	The Earth before and during the pear	11	1-11
B	The body on the tip — shape, rounding, release	12	12-23
C	The orbit	6	24-29
D	The maria and the openings	14	30-43
E	The craters and their source	14	44-57
F	The poles	10	58-67
G	South Pole-Aitken	12	68-79
H	The stripes and the Pacific	11	80-90
I	Mars and other bodies	16	91-106
J	Requirements and key tests	12	107-118
K	How to choose — three lists	—	—
Total		118	

How ready each topic is. Each part opens with a small table of its topics. Its last column shows, in colour, what a researcher needs to begin:

Readiness	Meaning
Public data	The topic can be done now, on data that are already public (catalogues, maps, gravity and topography grids, published isotope data).
New modelling	The data exist or none are needed, but a new calculation or simulation must be built.
New data	The topic needs a mission, returned samples, laboratory experiments or new observations.

How to use the paper. A reader can enter in two ways. One is by theme: a specialist in tides goes to Part C, a crater specialist to Parts E and F, a seismologist to topics 10 and 89. The other is by Part K, which sorts the topics into three lists for choosing. The first list holds the two key observations of the model. *The geometry of the exposure zones* asks whether the Moon’s crust thickens in order from the near-side contact, through the ring of the base, to the far side, and whether the oldest crater record follows the same three zones (topics 107 and 108). *The source of the craters* asks whether the metal and melt inside the craters carry the Earth’s isotopic signature, as returned material must, or a foreign one (topics 49 and 109). The second list holds what can be done now on public data; the third, what needs a large simulation, a mission or samples. A closing section names two subjects that lie outside this paper and are left as future work.

PART A

The Earth before and during the pear

Part A covers the parent body: the Earth before the Moon left it. In the model the Earth at that time was hot, rich in volatiles (substances such as water that turn to gas easily), spinning once in about five and a half hours, and still separating its iron toward the centre. From one region of it, near today's Kiritimati in the central Pacific, a pear-shaped extension of the Earth's own material rose toward the corotation line, and the Moon was built on its tip. These topics matter because they set the starting conditions of everything that follows: how large the parent was, where its corotation line lay, whether its deep melt was light enough to rise, whether it had the energy to lift the body and the pear, and whether the pear could stand. Most of them need new modelling of a state the series has already specified.

No.	Topic	Main tool	Readiness
1	Thermal expansion of the hot parent	Equation of state	New modelling
2	The stratified Maclaurin problem	Figure of a rotating body	New modelling
3	Core formation and the Hf-W history	Reservoir model	New modelling
4	Equation of state of the deep melt	Experiments, ab-initio	New data
5	Energy of the lift and of the parent	Thermal evolution	New modelling
6	Pressure test with the pear and flattening	Non-spherical field	New modelling
7	Construction rate: the feed flux	Pipe flow and freezing	New modelling
8	The pear's equilibrium figure (R9)	Free-surface figure	New modelling
9	The northward lean of the pear	Feed-path geometry	New modelling
10	The Earth's core during the pear	3-D hydrostatic model	New modelling
11	The classical fission route, recomputed	Fluid equilibria	New modelling

Part A at a glance. Ten of the eleven topics are calculations on a parent the series has already specified; one needs new laboratory data.

1 The thermal expansion of the hot parent

A hot body is larger than the same body cold, and a body full of dissolved volatiles is larger still. The size of the young Earth matters because, at a given mass, it sets the window of rotation periods in which the transfer can work. Paper 2 adopts an expansion of 120 km and shows that the model works over a range of values; a proper calculation would narrow that range.

The question. How much larger was the hot, volatile-rich early Earth than a cold one?

What the model predicts. An expansion of 120 km is adopted, and 98–520 km is admissible. The expansion sets the window of rotation periods in which the transfer can take place: 4.90–5.54 hours at $\Delta R = 120$ km (Paper 2).

Data. Estimates of the depth of the early magma ocean (a global layer of molten material); expansion coefficients of silicate melts.

Method. An equation-of-state integration of a hot, volatile-rich Earth. An *equation of state* relates pressure, temperature and density; integrated from the centre outward, it gives the radius.

Where in the series. Paper 2, Further work item 3; §D.3.

2 The stratified Maclaurin problem

A Maclaurin spheroid is the flattened shape taken by a uniform fluid body in steady rotation. The young Earth of the model was not uniform: its iron was sinking, so its inner part was becoming denser than its outer part. The position of the corotation line depends on how the mass is arranged inside, and this line is where the Moon starts its orbit.

The question. Where does the corotation line lie for a parent whose iron is sinking, computed self-consistently?

What the model predicts. 15,382–17,569 km, from $D = 3$ to $D = 1$, where D is the ratio of the density of the inner layer to that of the outer layer ($D = 1$ is a uniform body). At $D = 2$ the line lies at about 16,300–16,400 km. This is the starting orbit of Paper 4 (Paper 2).

Data. The parent of the series: volumetric radius 6,517 km, rotation period 5.5 hours, moment-of-inertia factor $k \gtrsim 0.397$. The factor k measures how much of the mass lies far from the axis: 0.4 for a uniform sphere, less for a body with a dense core.

Method. The Clairaut–Darwin–Radau theory of the figure of a rotating body, applied to a parent with descending iron.

Where in the series. Paper 2, Further work item 1; §A.4.1, §A.6.2. Paper 1 §F.2.

3 Core formation during the transfer, and the Hf–W reservoir history

Hafnium-182 is a short-lived radioactive isotope that decays to tungsten-182. Hafnium stays in the silicate while tungsten follows iron into the core, so the excess of ^{182}W in a reservoir records when its metal separated. The model needs the Earth's core to be still forming during the transfer, and one chronology must carry the tungsten signatures through the whole window of construction.

The question. Was the Earth's iron still descending during the transfer (centralisation $D \approx 2$), and can one chronology carry the tungsten signatures through the 600-Myr window?

What the model predicts. An essentially uniform parent at the start ($k \geq 0.397$). The core centralises during the transfer, and this shortens the day at release from 6.44 to 5.77 hours (Paper 2). The Hf–W excess was set early in the window and carried without reset (Paper 11).

Data. ^{182}W anomalies of terrestrial and lunar samples; Hf/W ratios.

Method. A reservoir model of metal-silicate separation over the 600-Myr window, with partial equilibration of metal and silicate.

Where in the series. Paper 2, Part D requirements box, §D.3. Paper 11 §D.2. Paper 1 §F.2 (“Hf-W reservoir history”) and §D.1 (orange row of Paper 2).

4 The equation of state of the deep, volatile-rich melt at 50-150 GPa

The pressure test of Paper 3 asks whether the deep source could push its melt up through the pear and into the body on its tip. The answer depends on one number: the density of a melt rich in water and carbon dioxide at the pressures of the deep mantle, 50-150 GPa (gigapascals; one GPa is about ten thousand times the pressure of the air at sea level). A lighter melt needs less pressure to be lifted, so the test turns on how light this melt is.

The question. Is a hydrous or carbonated silicate melt lighter than about $3,864 \text{ kg/m}^3$ along the ascent?

What the model predicts. The pressure test passes below $3,864 \text{ kg/m}^3$. At $3,500 \text{ kg/m}^3$ a margin of 10.49 GPa is left; at $4,000 \text{ kg/m}^3$ it does not pass (Paper 3).

Data. Shock-compression and diamond-anvil data on hydrous and carbonated melts; first-principles molecular dynamics.

Method. Experiments and *ab-initio* molecular dynamics (simulations from the quantum mechanics of the atoms) at the relevant compositions, giving the density threshold as a function of volatile content.

Where in the series. Paper 3, Further work item 3; §A.9–A.10; §D.1 row 1. Paper 1 §F.2 and §E.1 (“a light deep melt”). Paper 11 §D.3 (row R6).

5 The energy of the lift and the energy release of the parent

Lifting a lunar mass and a pear many times heavier out of the Earth’s gravity costs energy. The model takes that energy from the Earth itself: iron sinking to the core releases gravitational energy, as a weight released on a rope can turn a wheel. The topic asks whether the supply matches the cost, and how fast it was delivered.

The question. Does the evolving Earth release the work of lifting the body and the pear, and at what rate?

What the model predicts. The Moon’s lift costs of order 10^{30} J and the pear’s about $8 \times 10^{30} \text{ J}$ (5.4 times the Moon’s). The descent of the iron frees of order 10^{31} J (Paper 3).

Data. Parameters of core formation and of cooling under a steam atmosphere.

Method. A thermal-evolution model of an Earth with descending iron, contracting and cooling; from its output, the duration of the feed.

Where in the series. Paper 3, Further work item 4; §A.12; §C.9 (“Energy”); §D.1 row 3. Paper 1 §F.2 (“Energy balance”).

6 The pressure test repeated with the pear's mass and the flattened parent

The pressure test of Paper 3 was made in the field of a spherical parent. A parent spinning once in 5.5 hours is flattened, and its gravity is stronger in some directions than a sphere's. The flattening is measured by J_2 , the coefficient of the gravity field that describes the equatorial bulge. Paper 3 has already estimated its effect; what is left is to carry the test through with the pear's own mass included.

The question. Does the source pressure still lift and hold the body *and* the pear in the field of a flattened parent?

What the model predicts. With $J_2 \simeq 0.036$ the inward pull rises by 3% (5.4% at the equatorial surface). The cost of the lift rises by about 4 GPa, inside the margin of 10.49 GPa. The test has still to be rerun with the pear's own mass (Paper 3).

Data. The pear's geometry and mass (Paper 3 §C.7).

Method. The joint test of Paper 3 §A.9–A.13, carried out in a non-spherical field.

Where in the series. Paper 3 §C.9 (“Pressure”, “The parent's flattening”); §A.13.

7 The construction rate: feed flux over the window

A lunar mass had to pass up through the pear in the time the model allows. The flow of a viscous melt through a passage grows very steeply with the width of the passage — as the fourth power of its radius b , so that doubling the width multiplies the flow sixteen times. A broad passage is therefore the model's requirement, and the topic is to check that a passage of that width delivers the mass in time without freezing shut.

The question. Does the net feed deliver the internal mass in the time available (about 400 + 100 + 100 Myr, with 100 Myr as a sensitivity case)?

What the model predicts. The flux is sensitive to aperture as b^4 . A passage of about 1,000 km radius is required (0.46 lunar masses; a lateral load of order 10^{22} N) (Paper 3).

Data. Viscosities of the melt; radii of the passage.

Method. A model of pipe flow and freezing over the permitted ranges of viscosity and aperture.

Where in the series. Paper 3 §D.1 row 2; §A.11; §A.13. Paper 1 §E.1 (“A broad, massive, viscous connection”).

8 The pear's self-holding equilibrium figure and its budget of angular momentum (R9)

The pear is the Earth's own material standing out from the surface toward the corotation line. It must hold itself up: its base must be wide enough to carry it, and its shape must be one a rotating, internally pressurised Earth can keep. Paper 11 lists this as requirement R9. The present estimate uses round cross-sections of uniform density; a true equilibrium figure would replace it. The same figure also fixes how much spin the pear passes to the Moon.

The question. Does a rotating, internally pressurised Earth admit an equilibrium figure with a body at its tip — a base of about 9,000 km narrowing in one arc to a contact of 3,000 km, wholly inside the corotation line — and does that figure close the angular-momentum budget?

What the model predicts. The narrowest self-holding base grows from 7,800 to 8,800 km (at 3,000 kg/m³) between the start and release. The pear's mass is 8.8–12.1 lunar masses for bases of 9,000–11,000 km. The pear passes about a sixth of the system's angular momentum (the total amount of spin) to the Moon; this is taken from the Earth's spin and offset by the centralising core (Paper 3).

Data. The parent state of the series; no observations are needed.

Method. An equilibrium figure with a free surface, including the pear's own gravity along its axis and the internal flow. This replaces the present minimum-width estimate from round cross-sections of uniform density.

Where in the series. Paper 3 §C.7, §C.8, §C.9 (“The shape itself”, “Angular momentum and heat”). Paper 11 §C.6 (R9). Paper 1 §E.1 (R9, awaiting). Paper 2 §A.4.

9 The northward lean of the pear: oblique feed from a source north of the equator

The base of the pear lies near the equator, at about 1.9°N, yet the Moon was released from about 22.5°N. The tip therefore leaned north. Rotation pushes a raised mass toward the equator, not away from it, so the lean cannot come from the spin. The model places its cause in the feed: the deep source lay north of the equator and fed the pear obliquely.

The question. Can a deep source north of the equator feed obliquely enough to take the tip from a base near 1.9°N to about 22.5°N against the equatorward push of the rotation?

What the model predicts. The lean comes from the feed path, not from the rotation (Paper 3).

Data. The position of the base (Kiritimati) and of the Pacific low-velocity province, read — with reservation — as the returned pile.

Method. A geometry of the deep source and of the feed path in a rotating, flattened parent.

Where in the series. Paper 3 §D.1 (“The pear leans north”); §A.4; §B.1.

10 The Earth's core during the pear

A pear of about nine lunar masses standing on one side of the Earth moves the Earth's centre of mass toward it, and the dense core, floating in the mantle, follows. After the pear fell back, the core returned. The model asks whether this episode left a trace in the inner core, the solid centre of the Earth, whose eastern and western halves are known to differ in how fast seismic waves cross them.

The question. Was the Earth's core drawn 270–370 km toward the pear while the pear stood, and did it return after the pear fell?

What the model predicts. A displacement of 270 km at the start (9,000-km base) growing to 370 km at release (11,000-km base), and a return after compensation. A hemispherical structure of the inner core aligned with the pear's side is the record to look for (Paper 3).

Data. The east-west asymmetry of the inner core in seismic travel times; the age of the inner core. The test weakens if the inner core is much younger than the Moon.

Method. A three-dimensional hydrostatic model of the Earth with the pear standing and after its fall, following the deficit left in the source.

Where in the series. Paper 3 §E.5; Further work item 7.

11 The classical fission route, recomputed

The classical fission idea, from George Darwin onward, held that a spinning fluid Earth turns into an elongated ellipsoid (a Jacobi ellipsoid) and then into a pear that divides. It was rejected because the Earth-Moon system has far too little angular momentum for it. Paper 2 shows that the connected transfer of the LEF model needs almost exactly today's angular momentum. A modern computation of the classical route would make the comparison exact.

The question. What does a modern computation of the Jacobi sequence and its pear-shaped branch give for this mass and density?

What the model predicts. The classical route needs 2.74 times today's angular momentum at the Jacobi bifurcation (the point at which the elongated shapes branch off), against 1.007 for the connected transfer (Paper 2).

Data. Tabulated Jacobi and Poincaré sequences.

Method. A numerical sequence of rotating fluid equilibria, with the pear-shaped point verified.

Where in the series. Paper 2, Further work item 6; §A.6.5.

PART B

The body on the tip — shape, rounding, release

Part B covers the Moon while it was still attached: a foamed body on the tip of the pear, fed through its base and wrapped in the Earth's outer shell. In the model it passed through outward rounding, flattening and inward rounding; its contact with the pear narrowed from 6,000 to 3,000 km; and it let go at the corotation line. These topics matter because the attached stage is where the Moon's shape, its two different sides and its crust were made. They ask whether the body was stable, whether its shell could be stiff while its base stayed mobile, how it became round, how the contact failed, and what the near and far crusts should show. Two more ask what the foam and the contact left in the Moon as it is now: high-pressure phases in the samples from the contact zone, and porosity falling with depth. Most are calculations and simulations; three (topics 19, 21 and 23) can be checked now on public lunar data, and one (topic 22) on samples already returned.

No.	Topic	Main tool	Readiness
12	3-D simulation of the connected body	SPH / finite elements	New modelling
13	Stiff shell over a mobile base	Thermal-rheological balance	New modelling
14	From $a/c \approx 1.20$ to round	Elastic-viscous figure	New modelling
15	The drift of the release latitude	Viscous-layer integration	New modelling
16	Stefan adhesion and failure of the contact	Laboratory, numerical	New data
17	The trapped pressure at detachment	Momentum balance	New modelling
18	Survival inside the fluid Roche limit	Visco-elastic calculation	New modelling
19	The layered far-side crust	Central-peak compositions	Public data
20	The near-side crust over the contact	Thermal model, GRAIL	New modelling
21	KREEP as the torn edge of the sial (R12)	Th, K maps; anorthosites	Public data
22	High-pressure phases in contact-zone samples	Laboratory, Apollo 14 samples	New data
23	Whole-Moon porosity by depth	GRAIL porosity inversions	Public data

Part B at a glance. The attached stage is reached mainly by modelling; the two crustal topics and the porosity by depth can be begun on existing lunar maps; the high-pressure phases need laboratory work on Apollo 14 samples.

12 A three-dimensional simulation of the connected body

The series has specified the attached body completely: its mass, its foamed density, the width of the tip, the pressure of the feed. What it has not done is run that body forward in three dimensions and watch it evolve. Such a simulation is the most direct check of Paper 3: it would show whether the body stands, and whether it goes through the stages in the order the model gives.

The question. Is a body of the lunar mass, foamed to $1,300 \text{ kg/m}^3$ on a 6,000-km tip and fed through its base at 150 GPa, stable? Does it go through outward rounding, flattening and inward rounding, and release with the computed margin?

What the model predicts. A stable dome of about 3,650 km. The contact shrinks from 6,000 to 3,000 km. The order of the stages is well advanced before detachment (Paper 3).

Data. None needed; the initial state is fully specified in the series.

Method. A smoothed-particle (SPH) or finite-element simulation with a free boundary, together with one shared timing model for feed, cooling and failure.

Where in the series. Paper 3, Further work item 2; §D.1 rows “Stable attached body” and “Order of stages”; §A.5. Paper 1 §F.2, §E.3.

13 A stiff shell over a mobile base: the coupled thermal-rheological solution

The model asks two things of the Earth’s outer shell at once. It must be stiff enough to keep the craters made on it during the ascent, since those craters are the far side’s record. And the layer beneath it must stay soft enough for the shell to ride up on the growing dome. Viscosity, measured in Pa·s, is resistance to flow; the question is whether one cooling history gives a high viscosity above and a low one below, for long enough.

The question. Is there one rheological range in which the outer shell stays stiff enough to keep its craters while the interface beneath it stays mobile enough to ride up on the dome?

What the model predicts. A shell about 18 km thick, with viscosity $\gtrsim 10^{23} \text{ Pa}\cdot\text{s}$ through the ascent (a requirement, not a measurement), over a weak interface between sial and sima — the light outer layer of the early Earth and the denser layer beneath it (Papers 3, 11). The making of the record, its preservation and the rise must overlap in time (Paper 6).

Data. Viscosity laws for anorthositic and sialic crust; cooling under a steam atmosphere.

Method. A coupled thermal and rheological balance along the construction.

Where in the series. Paper 3 §D.1 row “Strengthening exterior and mobile base”; §A.7; §D.4 item 4. Paper 11 §D.1, §D.3 (“Rise and preservation”). Paper 6 §O.1 (“A record carried on the shell”). Paper 1 §E.1 (“A stiff shell”).

14 The step from $a/c \approx 1.20$ to round before release

Late in the attached stage, with a 5.77-hour day and a mean density of $2,600 \text{ kg/m}^3$, a fluid body would be a flattened Maclaurin spheroid with its equatorial radius a about 1.20 times its polar radius c . At release the Moon must be rigid and round. The series states this step as a requirement; the calculation that carries the body from one state to the other is a topic in itself.

The question. How does the rigid shell carry the body from the Maclaurin ratio of about 1.20 late in the attached stage (5.77 h, $2,600 \text{ kg/m}^3$) to a round body at release?

What the model predicts. At release the body is rigid and round: shear modulus $\mu \geq 10 \text{ GPa}$, axis ratio ≤ 1.04 . This is a requirement, not computed in the series (Papers 2, 7).

Data. None; a calculation.

Method. An elastic-viscous figure calculation of a shelled body under decreasing spin and increasing density.

Where in the series. Paper 7 §C.1 and front matter (“What it requires”). Paper 2 §B.7. Paper 1 §C.7.

15 The drift of the release latitude below 22.5°

The latitude at which the Moon was released becomes, in the model, its first orbital inclination i_0 . While the contact contracted from 6,000 to 3,000 km, the body sat on a viscous layer, and the rotation pushed it gently toward the equator. If it slid at all, it slid south, so the release latitude can only be lower than 22.5° . The size of that slide has not been computed.

The question. How far did the body slide toward the equator on the viscous contact layer during the contraction from 6,000 to 3,000 km?

What the model predicts. Anchoring holds the body on the wide tip; in the outward rounding it has freedom but little time. The drift can only lower the latitude, so 22.5° is an upper bound on i_0 (with 25° as a sensitivity case). Its size is not computed in the series (Papers 3, 4).

Data. Thickness of the layer d_0 (20–50 km), its viscosity, and the duration of stage 3.

Method. The tangential term $\omega^2 r \sin \varphi \cos \varphi$ (the equatorward push of the rotation at latitude φ), resisted by the viscous layer and integrated over the contraction.

Where in the series. Paper 3 §C.5 (“Why the body did not slide to the equator”); Further work item 1. Paper 4, Part E. Paper 1 §B.7.

16 Stefan adhesion and the time of failure of the contact

Two flat plates with a thin film of liquid between them are hard to pull apart: the liquid must flow into the widening gap, and that flow resists. This is Stefan adhesion. The Moon’s contact with the pear was such a film, a partly molten layer. How it finally let go — by cavities opening in it, by necking, or by a change from flowing to breaking — sets how far beyond the corotation line the Moon was released.

The question. How does a partially molten layer between two bodies let go — by cavitation, necking, the passage from viscous to brittle failure — and when?

What the model predicts. A slow phase, then a runaway once the gap reaches $d = 3d_0$. The release margin is $\Delta r \simeq 2d_0 \approx 210$ km beyond the corotation line ($d_0 \approx 105$ km), where the release-distance search of Paper 3, §C.5a finds the present inclination and the present eccentricity meeting, when a little more than half the Moon has crossed the line.

Data. Laboratory separation of plates joined by partial melt.

Method. Laboratory and numerical work on non-Newtonian Stefan adhesion (a fluid whose viscosity changes with the rate of flow), giving the range of the margin and the time of release.

Where in the series. Paper 3, Further work item 5; §C.5; §C.5a (the release-distance search); §D.1 row “Connection and release”. Paper 1 §F.2 (“time of failure of the contact”) and §D.1 (orange row of Paper 3).

17 The trapped pressure at detachment

Paper 3 names three actors in the separation. One of them is the pressure held beneath the body at the moment it let go, as a cork is pushed out by the gas behind it. Paper 4 computes the Moon’s release velocity without this term. The topic is to find how much it adds.

The question. What share of the Moon’s initial speed came from the pressure held beneath the body when it let go?

What the model predicts. The trapped pressure is one of the three actors of separation in Paper 3; it is left out of the release velocity of Paper 4 (Paper 7).

Data. None; a calculation.

Method. A momentum balance of the release with the trapped pressure, checking whether Paper 4’s release velocity needs a correction.

Where in the series. Paper 7, Further work item 5; §C.6. Paper 3 §C.7–C.8. Paper 1 §F.2.

18 Survival inside the fluid Roche limit: the deformation solution

The Roche limit is the distance inside which a planet’s tide pulls a moon apart. It is smaller for a rigid body than for a fluid one, because a rigid body resists the stretching. The young Moon was released at about 17,500 km (17,496 km, about 210 km beyond the corotation line; Paper 3, §C.5a), outside the rigid limit but inside the fluid limit. The model holds that it survived because it was already rigid. The series checks this with an order-of-magnitude estimate of the strain; a full calculation would replace it.

The question. Does a rigid body of radius 1,890 km survive 10^1 – 10^3 years at about 17,500 km without damaging deformation, heating or loss of mass?

What the model predicts. It lies about 7,200 km beyond the rigid Roche limit (10,314 km) and inside the fluid limit for 2,600 kg/m³ (19,971 km). It survives because it is rigid (Papers 2, 4).

Data. None; a calculation.

Method. A visco-elastic calculation that replaces the order-of-magnitude estimate of the strain.

Where in the series. Paper 2, Further work item 5; §D.1 (“Survival”); Appendix E. Paper 4, Part E (“deformation check open”). Paper 1 §D.1 (orange row of Paper 4).

19 The layered far-side crust

In the model the far side was built layer upon layer: gathered sial from the Earth’s surface and returning material that landed on the rising shell. Later layers were lighter and richer in fluids. A crust built this way should change in composition with depth, and the far side, built longer in this manner, should show the change more strongly than the near side. Central peaks of large craters bring up material from known depths, so they act as natural drill cores.

The question. Does the iron content of the far-side crust rise with depth, more strongly than on the near side?

What the model predicts. The far side is sialic, in the sense of the early Earth’s surface, and built in layers whose iron rises with depth. Its thickness does not depend on the local basin history (Paper 3).

Data. Central-peak compositions (Kaguya, Moon Mineralogy Mapper M³, LRO) with their depth of origin; Chang’e-6 material; GRAIL residuals after the basins are removed.

Method. Peak composition against depth of origin, far side against near side; a build model that predicts the steps.

Where in the series. Paper 3, Further work item 6; §B.7; §D.1 (“Layered far-side crust”); §D.4 item 8. Paper 1 §F.3 item 3.

20 The near-side crust over the contact

When the body peeled away from the pear, the ring of the lower dome came away with its sial and became the limb belt, the ring of crust around the near side. Over the 3,000-km contact itself the heat of the connection melted the sial and smoothed it. How deep that melting reached should set how thin the crust is over the contact compared with the belt around it.

The question. How deep did the heat of the contact melt the sial away, and does that give the thickness of the crust over the contact against that of the limb belt?

What the model predicts. The annulus of the lower dome peeled away with its sial (the limb belt). Over the 3,000-km contact the sial was melted and smoothed (Papers 3, 11).

Data. GRAIL crustal-thickness models.

Method. A thermal model of the contact, compared with the measured crust.

Where in the series. Paper 3, Further work item 8; §C.4a. Paper 11 §C.4.

21 KREEP as the torn edge of the sial (R12)

KREEP is a component of lunar material rich in potassium (K), rare-earth elements (REE) and phosphorus (P), concentrated on the near side around Oceanus Procellarum. The model reads it as the torn edge of the Earth's sial: when the body peeled away, the edge of the sial at the rim of the base was folded inward. If so, the sial left elsewhere — the most primitive anorthosites — should have lost the potassium and thorium that went into KREEP.

The question. Is KREEP placed at the rim of the base, around Procellarum, and have the most primitive anorthosites lost the K and Th of the Earth's sial?

What the model predicts. The torn edge of the sial was folded inward at the rim of the base when the body peeled away (Papers 3, 11).

Data. Lunar Prospector and Kaguya thorium and potassium maps; anorthosite compositions.

Method. The distribution of KREEP against the rim of the base; trace elements of primitive anorthosites.

Where in the series. Paper 11 §C.6 (R12). Paper 3 §C.10. Paper 1 §E.1 (R12, awaiting).

22 High-pressure phases from slow pressure in samples from the contact zone

While the body was attached, its lower face pressed against the top of the pear, and as the contact narrowed from 6,000 to 3,000 km the same load was carried by a smaller and smaller area: the pressure on the outer metres of that face rose as the contact shrank. The author's proposal is that this pressure was large but slow. The distinction matters for what the samples record. A shock wave, passing in a fraction of a second, turns feldspar into maskelynite, a glass formed in the solid state; a pressure of the same size applied slowly gives the minerals time to rebuild into dense crystalline phases instead — coesite and stishovite from silica, jadeite from feldspar. Returning material that landed made shock features everywhere on the Moon. Samples from the ground that was pressed against the pear should carry, in addition, the crystalline high-pressure phases. Apollo 14, at Fra Mauro, lies inside the contact cap, about 29° from the contact centre. Whether its samples contain these phases has not been checked.

The question. Do samples from the contact cap — Apollo 14 at Fra Mauro first — contain high-pressure phases formed by slow pressure (coesite, jadeite, stishovite), and not only shock glass?

What the model predicts. The pressure on the contact acted slowly, so it produced crystalline high-pressure phases rather than maskelynite, which requires a shock wave. Samples from inside the contact cap carry these phases; comparable samples from the belt carry shock features alone. Their absence from the cap, or an equal presence in the cap and in the belt, does not support the reading.

Data. Existing Apollo 14 samples of the Fra Mauro formation, 3.6°S 17.5°W (NASA lunar sample collection); as control, highland samples of the same kind from Apollo 16 and Apollo 17, both about 51° from the contact centre, in the belt.

Method. Raman spectroscopy, electron microscopy and microprobe analysis of thin sections, searching for coesite, stishovite and jadeite and recording their textures beside any maskelynite; the same procedure on the control samples, with the criteria fixed before the sections are read.

Where in the series. Not yet in the series; raised in the author's working notes (16.10.2026 collection). The contact cap (0–31° about 24.1°N 335.2°E) is that of Paper 3 §B.4 and Paper 11 §B.8; the narrowing of the contact is Paper 3 §C.4–C.5.

23 Whole-Moon porosity by depth: the record of the foam

In the model the body began as a foam, about 1,300 kg/m³ at the start of rounding, compacted to 2,600 kg/m³ at release and to 3,344 kg/m³ today. A foam that is compacted by its own weight closes its pores only where the pressure is high enough, and the weight of the overlying column grows with depth. The model therefore expects a Moon compacted at depth with a porous upper crust: the pores that survive are the remains of the foam near the surface. GRAIL measures porosity directly, through the bulk density of the crust: about 2,550 kg/m³, lighter than the grains it is made of, which corresponds to a mean crustal porosity of about 12%. Paper 8 read the porosity at the surface and at 10 km for South Pole–Aitken and its surroundings (topic 77); the same reading for the Moon as a whole has not been made.

The question. Does the porosity of the whole Moon, not only of South Pole–Aitken, fall with depth as a foam compacted by pressure should leave it, and at what depth do the pores close?

What the model predicts. The foam collapsed where the pressure sufficed; residual porosity survives in the upper few kilometres, and the deep body is compacted. Porosity that does not fall with depth, or that rises with it, does not support the reading. A fall with depth is also expected of pores opened by fracturing at the surface; the test therefore lies in the depth of closure and its spread over the Moon, set against a foam compacted from within.

Data. GRAIL bulk density, grain density and porosity grids (Wieczorek et al. 2013), with the linear and exponential depth models of Besserer et al. (2014). For reference, Paper 8 found 18.9–20.3% at the surface, and at 10 km 6.2–7.9% in the far-side highlands and 9.6–12.8% in the rest of the far side.

Method. Area-weighted means of porosity at the surface and at depth, in the exposure zones and over the whole Moon, with the maria and the large basins masked in every zone alike; the depth of closure compared with a compaction model of the foam under its own weight.

Where in the series. Paper 8 §B6 (porosity of South Pole–Aitken and the far side); Paper 7 §C.3 (compaction from 1,300 to 3,344 kg/m³); Paper 2 Appendix G, row E42 (volatiles and porosity). The whole-Moon reading is raised in the author's working notes (16.10.2026 collection). Topic 92 asks the same question of Phobos and Deimos.

PART C

The orbit

Part C covers the Moon after release. In the model it left about 210 km beyond the corotation line (Paper 3, §C.5a), at about 17,500 km from the Earth's centre, on a nearly circular orbit inclined at the latitude of its release, 22.5°, and the tides then carried it out to 384,400 km. Two quantities describe the orbit: the *inclination*, the tilt of the Moon's orbit against the Earth's equator or the ecliptic, and the *eccentricity*, how far it departs from a circle. These topics matter because the orbit is the model's link between the place of release on the Earth and the Moon we see today. They ask for the full integration from the release state, the Earth's tidal history, the first steps of recession, the cooling of a one-sided Moon, and the record of its early figure.

No.	Topic	Main tool	Readiness
24	Coupled thermal-orbital integration	Secular integrator	New modelling
25	Dissipation history of the Earth	Ocean-resonance models	New modelling
26	The onset of recession	Tidal integration	New modelling
27	Magma-ocean switch for a one-sided lid	Asymmetric thermal model	New modelling
28	The fossil figure	Closure geometry, GRAIL	New modelling
29	The ancient latitude, reconstructed	Structural reconstruction	New modelling

Part C at a glance. The orbit is reached by integration; the data (lunar laser ranging, the present elements, GRAIL) already exist.

24 The coupled thermal-orbital integration from the release state

Paper 4 follows the Moon from release to today with a reduced law and reaches 5.145° at today's distance, the measured value. The full test is an integration that follows the tides in both bodies as they cool, and passes through two transitions: the Laplace-plane transition, where the plane about which the orbit precesses changes from the Earth's equator to the ecliptic, and the Cassini state, the steady alignment of the Moon's spin axis with its orbit.

The question. Does the release state ($r_0 = 17,496$ km, $a_0 \approx 18,163$ km, $e_0 \approx 0.037$, $i_0 = 22.5^\circ$, a 5.77-hour day, J_2 scaled as ω^2) evolve to today's inclination of 5.145°, today's eccentricity and a distance of 384,400 km in 3.873 Gyr?

What the model predicts. The reduced law gives 5.145° at today's distance (5.788° from 25°). The full test passes through the Laplace-plane transition and the Cassini

state (Paper 4).

Data. Lunar laser ranging; the present orbital elements.

Method. A secular integrator (one that follows the slow, averaged change of the orbit) with time-dependent dissipation in both bodies. A short Newtonian integration checks the initial ellipse with any separation velocity and the flattened field.

Where in the series. Paper 4, Further work item 1; Part E rows “present inclination” and “initial ellipse”; §D.1. Paper 1 §F.2 and §D.1 (orange rows of Paper 4).

25 The dissipation history of the Earth

The Moon recedes because the tide it raises on the Earth is carried slightly ahead of it by the Earth’s spin and pulls it forward. How strongly depends on the Earth’s tidal response, written k_2/Q : k_2 measures how much the Earth deforms, and Q how little of that deformation is lost as heat (a low Q means strong dissipation). No single constant Q fits both today’s rate of recession and the age of the Moon, so Q must have changed, most likely with the shape of the ocean basins.

The question. What rate function $k_2/Q(t)$, starting from the 5.77-hour day, fits both today’s recession (3.8 cm/yr) and the age since release?

What the model predicts. No constant Q fits both: $Q \simeq 12$ gives the present rate, $Q \simeq 29$ gives the 3.87 Gyr (Paper 4).

Data. Tidal rhythmites (layered sediments that record ancient tides and day lengths); palaeo-day-length records; ocean-basin geometry.

Method. Ocean-resonance models of the early Earth.

Where in the series. Paper 4, Further work item 2; §D.2–D.3. Paper 2, Further work item 2. Paper 1 §D.1 (“Distance and clock”, awaiting).

26 The onset of recession

The Moon was released only a few tens of kilometres beyond the corotation line. Outside that line the Earth’s tide pulls the Moon forward and it moves outward; inside it, the tide would pull it back. The model requires that recession begin at once. A tidal integration from the release state would show the rate in the first orbits.

The question. At what rate does the Moon start to recede from a release a few tens of kilometres beyond the line?

What the model predicts. $\langle \dot{a} \rangle > 0$ from the first orbit, where $\langle \dot{a} \rangle$ is the average rate of change of the orbital radius (Papers 2, 4).

Data. None; a calculation.

Method. A tidal integration with frequency-dependent rheology in both bodies, starting from the release state of Paper 3.

Where in the series. Paper 2, Further work item 4; §B.8. Paper 4 §B.2.

27 The magma-ocean switch for a one-sided lid

The young Moon was partly molten, and a molten Moon dissipates tidal energy very differently from a solid one. Paper 4 shows that the survival of the inclination depends on when this “switch” from molten to solid took place. Published models of the lunar magma ocean are symmetric; the model’s Moon is not. Its lid was thick on the far side and thin on the near side, and would have cooled differently.

The question. When did a Moon with a lid thick on the far side and thin on the near side finish solidifying, and was that before 20 Earth radii?

What the model predicts. The survival of the inclination depends on this switch (Paper 4).

Data. Published magma-ocean models, which are symmetric.

Method. A thermal model of a Moon with an asymmetric lid.

Where in the series. Paper 4, Further work item 4; §D.2.

28 The fossil figure

The Moon’s shape departs slightly from the shape a fluid body would take today; it is a “fossil” from an earlier time. The departure is described by two coefficients of the degree-2 gravity field: J_2 , the polar flattening, and C_{22} , the elongation toward the Earth. In the model the body did not acquire this shape through a later tidal lock; it kept the figure set when the dome closed, and it kept one face toward the Earth from the attached stage onward.

The question. Does the shape left by the closure of the dome match the Moon’s present degree-2 figure, and is the synchronous rotation kept from the attached stage?

What the model predicts. The body carries its figure from the closure, not from a later tidal lock. It kept one face to the Earth from the attached stage (Paper 4; Paper 11, R4).

Data. GRAIL degree-2 gravity; LOLA shape.

Method. The closure geometry of Paper 3 gives a predicted J_2 and C_{22} , compared with the present values.

Where in the series. Paper 4, Further work item 5; §C.3. Paper 11 §A.4, §B.4 (R4).

29 The geographic link: the ancient latitude reconstructed independently

In the model the Moon’s first inclination is the latitude of its release, $i_0 = |\lambda|$, and that latitude is fixed by the centre of the contact on the Earth, 22.5° . Paper 4 uses this value; it is not yet reconstructed independently. A reconstruction from the structure of the Pacific source region and from the Moon’s own rotation, made without fitting to the orbit, would test the link between the place on the Earth and the orbit in the sky.

The question. Can the latitude of the Moon’s centre of mass at release be reconstructed from structure and rotation alone, without fitting it to the orbit?

What the model predicts. 22.5° , the centre of the 3,000-km contact. The identity $i_0 = |\lambda|$ holds independently of the reconstruction (Paper 4).

Data. The structure of the Pacific (topics 80–90); the centre of the contact on the Moon.

Method. A structural and rotational reconstruction.

Where in the series. Paper 4, Part E, row “Geographic link”. Paper 1 §D.1 (awaiting row of Paper 4).

PART D

The maria and the openings

In the model a mare is not a basin flooded after an impact; it is an *opening* over a *feed dome*: a place where hot, volatile-rich melt rose from below through the shell of the body sitting on the Earth's pear, and later poured out as basalt (Paper 3, Paper 5). The openings were exposed in a fixed order as the front of the retreating cover passed over them, and each sealed when the melt supply that kept it open failed. This part collects the topics that test that picture mare by mare: whether each opening lived long enough, in what order the openings sealed, what thorium and titanium record above the feed domes, what the rims and collars of the maria show, and what the openings left beneath and around them: the caves as vapour voids, the jump of the crust by the age of the basin, the diameter of an opening by how long it was fed, the rim as a layered record, the crests on the side of the plain, and the gravity of the craters that vanished into the active maria. They matter because the maria are the model's most visible claim on the near side: if the openings did not behave as openings, the near-side asymmetry needs another cause.

The table lists the fourteen topics. The last column gives readiness: **green** means the work can be done now on public data; **orange** means it needs new modelling; **blue** means it needs a mission, samples or data not yet in hand.

No.	Topic	Readiness
30	The engine of the openings: critical flux and times of sealing	New modelling
31	The order of sealing	Public data
32	Thorium at high resolution over the feed domes	Public data
33	The rim ring of the volatile-rich maria	Public data
34	Gradual exposure within one mare	Public data
35	Vents and conduits: the character of an opening by its zone	Public data
36	The titanium part of Study 13	Public data
37	The collar of the open far maria	Public data
38	The pits and caves of the Moon: vapour voids, not lava tubes	Public data
39	The crust jump under an opening, by the age of its basin	Public data
40	The diameter of an opening by the duration of its feeding	Public data
41	The rim of a mare as a layered record: rim height and the duration of ejection	Public data
42	Blunt or sharp: the crest where a large crater's rim is missing on the side of the plain	Public data
43	Gravity traces of the craters that vanished into the active maria	Public data

Thirteen of the fourteen topics can be started on maps and catalogues that are already public. Only the first, the engine of the openings, needs a calculation that has not been written.

30 The engine of the openings: critical flux and times of sealing

An opening stays open as long as the melt passing through it brings in heat as fast as the walls lose it to the cold shell around them; when the flow weakens below that level the melt in the conduit freezes and the opening seals. Paper 5 states this balance as its equation (4) and requires that every mare-forming opening outlived the moment the front of exposure reached it. The calculation of how long each opening actually lived has not been made.

The question. For each mare, did the opening stay alive until the retreating front exposed it?

What the model predicts. An opening seals when the melt flux falls below the *critical flux*, the flux at which the heat carried in balances the heat lost to cooling (Paper 5, eq. 4). The model requires that the openings outlived their exposure.

Data. Mare areas, depths and ages; the exposure generations of Paper 5, §I.4.

Method. A calculation of the critical flux and the time of sealing for each mare, set against the time at which the front exposed it.

Where in the series. Paper 5, Further work item 1, §§H.3, I.6, M.3 (“The engine”); Paper 1, §F.2, table of open computations (“The engine of the openings”).

31 The order of sealing

If the openings were fed from the contact, the region that touched the Earth's column last, then the openings nearest the contact were the last to lose their supply. Their youngest basalts should therefore be younger than those of the maria farther away. Thorium has to be held fixed in such a test, because the thorium-rich region of the near side (the region enriched in potassium, rare-earth elements and phosphorus, called KREEP) stays warm longer for reasons of its own radioactive heat.

The question. Does the youngest basalt of each mare grow younger toward the contact centre once thorium is held fixed?

What the model predicts. The contact maria sealed last (Paper 5).

Data. Crater-count and radiometric ages of the youngest units of each mare (for example the unit ages of Hiesinger and co-workers); thorium maps.

Method. Regression of the youngest age on the angular distance from a centre fixed before the data are examined, with thorium as a covariate.

Where in the series. Paper 5, Further work item 6, §§K.2, M.3; Paper 1, §F.3, item 8.

32 Thorium at high resolution over the feed domes

Paper 5 requires that thorium is lowest exactly over the channels of the feed domes, because the melt that rose through them came from below the thorium-bearing layer and diluted it. The thorium maps from orbit are blurred by the wide footprint of the detector; a reconstructed (deconvolved) map, in which that blurring is mathematically removed, sharpens them to about 26 km. At that resolution the channels can be separated from the rings around them.

The question. Is thorium lowest exactly over the channels of the feed domes?

What the model predicts. The minimum lies over the channels, as Paper 5, §J.6 requires.

Data. The reconstructed thorium map at 26 km.

Method. Thorium over each dome against the rings around it, at the sharper resolution.

Where in the series. Paper 5, Further work item 5, §J.6; Paper 1, §F.3, item 8.

33 The rim ring of the volatile-rich maria

The model reads the margins of the maria as built by the spray of their own openings: material thrown out while the opening was active, which landed nearby and left a ring of small craters on the rim. Paper 5 tested this for all rims together and ruled it out: not every rim carries such a ring. What remains is the narrower and stronger form: the ring belongs to the maria that were richest in volatiles, since it was the volatiles that drove the spray.

The question. Do the maria richest in volatiles carry a ring of small craters on their rims?

What the model predicts. Not every rim carries a ring (Paper 5, §M.1). The ring belongs to the volatile-rich maria, whose spray built the margins (Paper 5, Paper 6).

Data. Small-crater catalogues; maps of pyroclastic and dark-mantle deposits (fine volcanic glass thrown out by gas-driven eruptions); hydration maps from the Moon Mineralogy Mapper (M³).

Method. Small craters on the mapped rim against the ground outside, with the maria removed on both sides, set against a measured volatile content for each mare.

Where in the series. Paper 5, Further work item 2, §§F.3, H.2, M.1, M.3; Paper 6, §O.1 (“The ring of active spray”, open).

34 Gradual exposure within one mare

The front of exposure moved across the body over time. A large mare that the front crossed was therefore not exposed all at once: one side was open while the other was still covered. The side exposed first should carry a longer record: more craters, more of them filled, a different preservation.

The question. Does a large mare that the front of exposure crossed differ from one side to the other, in the direction of exposure?

What the model predicts. The mare was exposed side by side over time (Paper 5).

Data. Crater preservation, filling and structure across large maria.

Method. Profiles across the mare along the direction of exposure.

Where in the series. Paper 5, §§I.3, M.3.

35 Vents and conduits: the character of an opening by its zone

The model places the openings in three zones of the body on the pear: the crown and the flank of the upper dome, which were exposed and ejected material; and the region under the base, which stayed covered and only conducted melt through it until release. An opening that ejected and an opening that only conducted should look different today. The model reads the difference in the mascons, the strong positive gravity anomalies (mass concentrations) found under many near-side maria: mascons with rings in the belt, mascons without rings in the contact, and basins on thick crust beyond.

The question. Do openings that ejected while exposed (crown and flank) differ measurably from openings that only conducted under cover (under the base)?

What the model predicts. In the belt, mascons with rings; in the contact, mascons without rings; beyond, basins on thick crust (Paper 3, Paper 5, Paper 11).

Data. Secondary-crater fields; crustal thickness beneath each basin; composition of the earliest fill; GRAIL gravity gradients; a rim height index.

Method. Groups fixed before the rings are examined; a full basin list with a height index; comparison with models of impact, fill, subsidence and intrusion.

Where in the series. Paper 3, Further work item 9, §B.5; Paper 5, §§D.6, M.3; Paper 11, Further work item 6, §§C.3, D.3 (“Rings and openings”). Related: topic 108 (tests T3, T4).

36 The titanium part of Study 13

Study 13 of Paper 5 asked whether the melt of the contact, rising from deeper, diluted thorium relative to titanium more than the melt beyond it. The thorium part of the study held. The titanium part was expected but did not separate the zones: Imbrium, the main exit, does not separate, and the crater Copernicus H shows the opposite sign. The study stays orange until the titanium maps are read at a finer scale.

The question. Is the thorium-to-titanium ratio lowered more within the contact than beyond it?

What the model predicts. Expected, but it did not separate the zones. Imbrium does not separate; Copernicus H shows the opposite. The thorium part held (Paper 5).

Data. Thorium and TiO₂ maps.

Method. Titanium at higher resolution (LROC Wide Angle Camera, M³), with maria and plains separated within each zone.

Where in the series. Paper 5, §§J.4, M.2 (Study 13, orange); Paper 1, §D.1.

37 The collar of the open far maria

If the margins of a mare were built by layers of its own returning material, the ground just around it should stand raised, as a collar. Paper 5 found such a collar around the far-side maria taken together, and most clearly around the buried ones. Around the ten open far-side maria alone (median collar 207 m) it has not yet been shown to stand above the control.

The question. Does the raised collar stand above the control around the open far maria alone?

What the model predicts. The margins were built by layers of the mare's own returning material. A collar is found around the far maria together, and most clearly around the buried ones, but not yet around the 10 open far maria (median 207 m) (Paper 5).

Data. LOLA and SLDEM topography (the laser altimeter of the Lunar Reconnaissance Orbiter, merged with the Kaguya stereo terrain model).

Method. Ring profiles with a larger or better-matched control.

Where in the series. Paper 5, §§F.3, M.2 (Study 16, orange); Paper 1, §D.1.

38 The pits and caves of the Moon: vapour voids, not lava tubes

Images from orbit show steep-walled pits in the lunar surface, and in 2024 radar data showed a cave passage opening beneath the pit of Mare Tranquillitatis. In the literature the pits of the maria are skylights into lava tubes: channels left when the surface of a lava flow froze and the melt beneath it drained away. The author's proposal is different: the pits and caves are voids left by trapped vapour that broke out. The material of the model was rich in water and other volatiles, and when the far-side openings sealed the pressure beneath them was trapped (Paper 5, §I.5); vapour held in the shell and forcing its way out leaves voids behind it. The two readings differ in

shape and in place. A lava tube is a long, shallow tube that runs with the flow, and it exists only where lava flowed. A vapour void is a deep, dispersed network, and it can lie wherever vapour was held. The pit of Mare Tranquillitatis lies within the mouth of its opening. The test has not been made.

The question. Are the pits and caves of the Moon voids left by trapped vapour that broke out, rather than lava tubes?

What the model predicts. Vapour voids: deep, dispersed networks rather than long, shallow tubes, and not confined to ground where lava flowed. The decisive case is a cave on the far side, far from any basalt: it cannot be a lava tube, since no lava flowed there.

Data. The LROC catalogue of lunar pits (Wagner and Robinson 2014, and its later updates), with the setting of each pit; the LROC mare map; LROC Narrow Angle Camera images of the pit walls; Mini-RF radar, with which the passage beneath the Tranquillitatis pit was found (Carrer and co-workers 2024).

Method. Each pit is placed by its setting and by its distance from the nearest mapped basalt, and the far-side pits far from basalt are listed apart. In the literature the pits outside the maria are read as collapses in the cooled melt of craters, so the setting alone does not decide; for the pits with images of their walls or radar beneath them, the shape of the void is read as well: long and shallow along a flow, or deep and branching.

Where in the series. Not yet in the series; raised in the author's working notes (16.10.2026 collection). Related: Paper 5, §I.5 (the pressure trapped beneath the sealed far-side openings); Paper 8, §B6 (voids left near the surface by escaping gases).

39 The crust jump under an opening, by the age of its basin

Under the centre of an opening the crust is thinner than in a ring around it: the feed dome was pushed up from below, raised the dense mantle beneath the opening and thinned the light crust above it. Paper 5 calls the difference the *crust jump* and measured it opening by opening: 29 of the 36 marked openings show a jump of 8 km and more, with a median of 17 km, against 4 of 169 ordinary craters, with a median of 1 km. The author's proposal adds time to this measurement. A basin that formed while the Moon was still hot did not keep its jump: the warm material beneath it flowed slowly back, and the jump relaxed. A young basin kept more of it. The literature reads the subdued gravity of some old basins in the same way, as viscous relaxation in a warm early Moon (for example Kamata and co-workers, 2013). Two cautions shape the test. The basins must be ordered by age without the calibration of crater counts to years (Neukum's), which assumes a constant rate of bodies from outside, the assumption the model does not accept. And a large basin has a larger jump for its size alone, so size must be held fixed.

The question. Is the crust jump under an opening, relative to its size, larger in young basins and smaller in old ones?

What the model predicts. Yes. In an old basin, formed while the Moon was hot, the jump relaxed; a young basin kept more of it.

Data. The crust jumps of Paper 5, §D.2 (the four GRAIL crustal-thickness models, averaged; the centre to 0.3 of the radius against the ring at 1.3–2.0 radii); the relative

order of the basins by superposition, what lies on what (Wilhelms 1987), and by the density of the craters superposed on them (Fassett and co-workers 2012).

Method. The jump divided by the radius, or compared between basins of similar size, against the order by superposition and by crater density, for the openings that show the jump; a rank correlation for each ordering. Neither ordering is converted to years.

Where in the series. Paper 5, §D.2 (Study 3), which measures the jump itself but not its dependence on age. The dependence on age is not yet in the series; raised in the author's working notes (16.10.2026 collection).

40 The diameter of an opening by the duration of its feeding

An opening that fed for long under cover, in heat and under pressure, can grow wider than one that was exposed and cooled early: a hot flow widens its path, as running water widens a channel in ice. Paper 5 states this as a prediction, not an assumption: the diameter of an opening is a function of the history of its feeding, of the pressure, temperature, flux and viscosity of its melt, and of its exposure, $D = F(\text{history of feeding}, P, T, Q, \eta)$. The openings fall into three generations by that history (Paper 5, §I.4): generation I on the far side, exposed from the start and sealed early; generation II in the belt, a mouth first and an exit later; generation III in the contact, covered until near release. Paper 5 read one side of the prediction on its catalogue: the six largest feed domes, 450–909 km across, all lie on the near side, and the median diameter is 375 km there against 227 km on the far side, where the largest is Orientale, 435 km. The order of the diameters by generation, which is the test of the prediction itself, has not been made.

The question. Are the openings that fed longest under cover wider than those that were exposed and cooled early?

What the model predicts. The diameter of an opening is ordered by the duration of its feeding (Paper 5, §I.6): the openings that fed longest under cover are the widest.

Data. The diameters, zones and generations of the feed domes and maria in Paper 5, Appendix A; the GRAIL gravity field from which the domes were measured; the distance of each opening from the contact centre, which reads when it was exposed (Paper 5, §I.1).

Method. Diameter against generation and against distance from the contact centre, within the near side as well as across the two sides, so that the comparison does not rest on the difference between the hemispheres alone; buried and open domes are measured alike, as domes.

Where in the series. Paper 5, §§I.4, I.6 ("The size of an opening as a memory"). Related: topic 30 (the engine of the openings).

41 The rim of a mare as a layered record: rim height and the duration of ejection

In the literature the high ground around a basin is its rim, raised in one event by the blow that dug the basin and by the collapse that followed. In the model the margins of a mare were built from outside, layer on layer, by the material the mare itself threw out (Paper 5, §F.3). Material that fell back into the mare vanished in it; material that fell

on the margins stayed there and left a mark of its time. Two consequences follow. The longer an opening threw material, the higher its margins should stand. And margins built in this way are layered, with ages spread over the time of ejection, whereas the rim of a single collapse has one age. Paper 5 measured that every large floor lies below its rim (16 of 16, by a median of 3.4 km) and found a raised collar of returning material around the far maria (topic 37). Whether rim height follows the duration of ejection, and whether the rims are layered, has not been tested.

The question. Are the rims of the maria built of layers whose ages spread over time, and does the height of a rim grow with how long its mare threw material out?

What the model predicts. The higher the rim, the longer the ejection lasted. The rim is layered, with a spread of ages; a rim made by a single collapse after an impact would have one age.

Data. Rim heights from LOLA and SLDEM2015, read as in Paper 5, Study 6; crater-count ages of the units on each rim; LROC Narrow Angle Camera images and Moon Mineralogy Mapper (M³) spectra of the walls of the rim massifs; the order of exposure and the generation of each opening (Paper 5, §I.1, I.4).

Method. Rim height above the floor and above the land around, against the time each opening threw material: from the order of exposure, and from the times of sealing once topic 30 provides them. On the rims, a search for layering in the massif walls and for a spread of ages between the units of one rim.

Where in the series. Paper 5, §F.3 (the margins built of layers of returning material; Study 16), §F.1 (the floor below the rim). Related: topics 33 (the rim ring) and 37 (the collar).

42 Blunt or sharp: the crest where a large crater's rim is missing on the side of the plain

On the plains of the contact the large craters have lost their rims on the side that faces the plain. The literature reads a low rim on a mare plain as flooding: basalt rose around the crater and hid its lower slopes, as water rising around a sandcastle hides its base but leaves its top untouched. The model reads it as heat: the plain of the contact, heated from the Earth beneath it, wore away the rim where it touched it and lowered the crest itself. The two readings part at the crest. A flood rises along the outer flank and does not reach the top, so a flooded crest stays sharp; a crest worn by heat is blunt. Paper 5 and Paper 6 measured this (Study 15). On the plains of the contact the rim is missing on 24% more of the directions that face the plain than of those that face the highland, and the crest that survives on the side of the plain is blunter: its sharpness lower by 35 m/km², its width 50 m below the top larger by 0.14 km, and its angle wider by 5.3°. On the plains beyond the contact the two sides differ by little. What remains open is the direct comparison: matched crater against crater, at the same diameter, latitude and interior depth, only four pairs of the contact and beyond could be formed, too few to compare the two groups.

The question. In a matched sample of craters of equal interior depth, are the crests on the plains of the contact blunter than on the plains beyond?

What the model predicts. Blunt crests on the plains of the contact, where the plain was hot; sharp crests beyond it, where only flooding acted (Paper 5, §M.3).

Data. SLDEM2015 at 512 pixels per degree (60 m); where they exist, the finer terrain models made from LROC Narrow Angle Camera stereo images; the Wang & Wu crater catalogue; the LROC mare map.

Method. The crest of each crater read on radial profiles for sharpness (the curvature at the top), width 50 m below the top and the angle between the inner and outer slopes, as in Study 15, on a larger sample matched crater against crater in diameter, latitude and interior depth between the plains of the contact and the plains beyond, on the finest elevation model.

Where in the series. Paper 5, §§G.6, M.3 (Study 15); Paper 6, §E.6 (Study 15, “Directions for further research”).

43 Gravity traces of the craters that vanished into the active maria

On the floors of the maria of the contact, 703,000 km², not one crater of 20 km and more remains, melted or sharp (Paper 6, §D.2). In the model the craters that landed there while the maria were active entered them and vanished; they are in no catalogue. They differ from the melted craters seen as rings on other mare floors, under which Paper 6 found a small excess of mass with no edge (Study 14). Whether the vanished craters left any trace in the gravity field has not been examined. The author’s expectation is clear: there is no body beneath them, unless the edge of a crater still shows above the ground, which is another case. If any mass remains, it is that of the returning material that landed, vanished into the mare and left its mass there, without the shape of a body. The literature reads ring-shaped gravity features beneath the near-side maria as craters buried by later basalt (Evans and co-workers 2016); in that reading a crater under a mare is a body with the shape of the crater, and a body with a shape has an edge.

The question. Did the craters that vanished into the active maria of the contact leave a mark in the gravity field?

What the model predicts. No body with the shape of a crater beneath the floors of the maria of the contact: no ring of steep gravity at the edge of a crater, except where the edge of the crater still shows above the ground. At most an excess of mass without shape, as under the melted craters (Paper 6, §D.3).

Data. The GRAIL crustal model and Bouguer field (the gravity after the pull of the visible relief is removed), and gravity fields of higher degree; the 34 maria and the cores of their feed domes (Paper 5, Appendix A); the buried craters identified in the GRAIL field by Evans and co-workers (2016).

Method. A search of the floors of the maria of the contact for crater-sized rings in the Bouguer field and its gradients, read against random points on the same floors so that the dome beneath is removed, as in Study 14; the rings of Evans and co-workers placed by zone and read for an edge, as the steepness of the gravity at the edge against inside and outside it.

Where in the series. Paper 6, §D.2 (no crater of 20 km and more on the floors of the maria of the contact), §D.3 (Study 14, the mass under the melted craters, without an edge).

The craters and their source

The model's craters were made by returning material: material thrown from the openings of the Earth and of the body itself, which landed on the shell at about the speed it left (Paper 6). Some 99% of the lunar craters are, in this reading, of returned terrestrial material, and the foreign mass that external bodies would leave is not found in the crust. This part collects the topics that would turn that reading into a calculated chain, from the exit velocity at the opening, through the passage of the steam atmosphere and the shock at landing, to the size distribution of the surviving craters, and the topics that read the source in the craters themselves: their melt, their iron and their distribution in longitude. Two more test the clock and the surface of the craters: whether crater-count ages run older than direct ages of the same surface, and whether the rays of the young craters lie within the surface rather than on it. It is one of the two places where the model can be decided (Part K): whether the material inside the craters is foreign or returning.

No.	Topic	Readiness
44	The exit velocity from the openings	New modelling
45	Passage through the steam atmosphere	New modelling
46	Shock in a hot, layered target; scaling at $g = 8.25$ m/s ²	New modelling
47	The trend in a series of events	New data
48	The crater size distribution, propagated	New modelling
49	Seeing the returning body, not the ground	New data
50	Captured ejecta after release	New modelling
51	The longitude record: landing strength or maria?	Public data
52	The trailing-side excess: the yield of craters near 90°E	New modelling
53	The Earth as the last scatterer	Public data
54	Material after release poorer in iron	Public data
55	Iron of the high and low floors	Public data
56	Crater-count ages against direct ages	Public data
57	The rays of young craters: material within the surface	Public data

The colours follow the chain. The physics of the flight (44–48, 50, 52) needs new calculations; the reading of the craters themselves (51, 53–57) can begin now on public maps; the two topics in blue need measurements on material in hand.

44 The exit velocity from the openings

Paper 6 takes the energy of ejection from the volatiles: water and carbon dioxide dissolved in the melt at depth come out of solution as the pressure falls, and the gas drives the melt out of the opening. Paper 6 shows where the material landed, but it does not prove the speed. For the craters to form as the model reads them, the returning material must land at 2-8 km/s, and the openings must therefore have thrown it at about that speed.

The question. Does explosive decompression of a volatile-rich melt at the source pressures of Paper 3 give exit speeds such that material returns at 2-8 km/s?

What the model predicts. The energy of ejection comes from the volatiles. The speed of the returning material is a requirement, not proved in Paper 6 (Paper 6, Paper 11).

Data. Volatile contents (requirement R6); source pressures (Paper 3).

Method. A model of explosive decompression that gives the distribution of exit velocities.

Where in the series. Paper 6, Further work item 2, §§J.1, O.1 (row “Ejection, passage and fast landing”); Paper 11, §D.1 (Paper 6 row).

45 Passage through the steam atmosphere

On its way back, the thrown material had to cross the dense vapour atmosphere of the scenario, with a base pressure of order 10 to 1,000 bar. A small or dispersed body would be slowed and broken in it; a concentrated one could pass through and meet the shell. Paper 6 gives one example only: a body one kilometre across, crossing a column with 100 bar at its base, keeps about half its speed. The range of sizes that arrive intact, with heating and break-up included, has not been computed.

The question. Which returning bodies of 0.1-10 km reach the shell intact through a 10-1,000-bar atmosphere?

What the model predicts. A concentrated returning body passes and meets the shell (Paper 6).

Data. None needed; this is a calculation.

Method. Coupled gravity-drag trajectories with heating and break-up.

Where in the series. Paper 6, Further work item 3, §J.3.

46 Shock in a hot, layered target, and crater scaling at $g = 8.25 \text{ m/s}^2$

The shock pressure reached when a body lands depends on both materials, through their Hugoniot curves (the measured relation between shock pressure and compression for each material). Paper 6 estimated it as basalt landing on basalt. The model’s target is different: a cold sialic shell (the light, silica- and aluminium-rich outer layer) over a mobile, hot base, on a body whose surface gravity at that stage was 8.25 m/s^2 , about five times the gravity of the Moon today. Both the shock and the size of the crater it makes need to be recomputed for that target.

The question. What shock pressure and crater size does a dense returning body produce on a cold sialic shell over a mobile base?

What the model predicts. This calculation replaces the basalt-on-basalt estimate of Paper 6.

Data. Hugoniot data for sial and basalt.

Method. Impedance matching (solving for the common pressure and particle velocity at the contact of the two materials) and crater scaling laws for the shell's gravity.

Where in the series. Paper 6, Further work item 4, §J.2.

47 The trend in a series of events

Paper 6, eq. (14), relates the shock in a returning body to the height of the target on the body. The trend it predicts depends on the path: on the source of the material, on the spin and on the field at the time. The model does not predict one general trend for all events; the comparison is made within a series of events that share one source, spin and field.

The question. Do shock indicators change with target height as eq. (14) predicts, for one stated source, spin and field?

What the model predicts. The trend is path-conditional, as stated in Paper 6, and is read within a series of events of one source, spin and field.

Data. Shock measurements in units of identified age and origin.

Method. Controls on material, angle and position within an event.

Where in the series. Paper 6, §§O.1 (row 2), K.3.

48 The crater size distribution, propagated

The size-frequency distribution of craters, the number of craters per unit area as a function of their diameter, is the standard fingerprint of a crater population. In the model it should follow from the sizes and speeds at which material left the openings, after break-up in flight, landing, saturation (the state in which new craters erase old ones as fast as they form) and burial by later fill. Paper 6 keeps the distribution as a constraint on the model, not yet as a test it has passed or failed.

The question. What size-frequency distribution follows from the ejected sizes and speeds after break-up, landing, saturation and burial?

What the model predicts. For now a constraint, not a failed test (Paper 6).

Data. Crater catalogues (Robbins; Head and Kadish; Wang and Wu).

Method. A forward model from the source to the surviving craters, in which neither saturation nor a constant flux is assumed.

Where in the series. Paper 6, §P.2.

49 Seeing the returning body, not the ground

This topic is one of the two key observations of the model in Part K. Paper 5 found that the ground around a mare carries the mare's iron: FeO falls from 6.9 to 3.1 wt% within 150 km of the mare, against 2.3 wt% in the control. Yet a crater made by that material looks like its surroundings, because the landing threw the thin veneer aside and exposed the ground beneath. The signature of the returning body is therefore not on the surface around the crater; it must be read in the melt formed at landing, which mixes the landing body with the target.

The question. Can the share of the returning material inside a crater be identified, and does it carry the iron and thorium signature of its source mare?

What the model predicts. The ground around a mare carries the mare's iron (6.9 → 3.1 wt% FeO within 150 km; control 2.3), but the crater looks like its surroundings because the landing threw the veneer aside. The returning body's signature is carried in the melt (Paper 5, Paper 6).

Data. Melt and glass deposits inside craters; deconvolved thorium; future samples.

Method. Crater interiors read zone by zone; melt and glass compositions against the candidate source mare; a mixing model of returning body and target.

Where in the series. Paper 6, §§L.2, L.3, O.1 (rows "Terrestrial source" and "The maria as the source"); Paper 5, §§C.7–C.8. Related: topic 109.

50 Captured ejecta after release

The Earth did not stop throwing material when the Moon was released. A Moon only a few Earth radii away would have captured part of that later ejecta, and those landings form a separate population: the few young craters on the maria. How large a fraction it captured depends on the launch speed and direction, and has not been computed.

The question. What fraction of the Earth's post-release ejecta did a Moon at a few Earth radii capture, as a function of launch speed and direction?

What the model predicts. The Earth went on throwing after release; part of it reached the Moon (Paper 3, Paper 6).

Data. The few young craters on the maria; their shock and size record.

Method. An orbital capture calculation, together with the record that separates this population from later bodies arriving from outside.

Where in the series. Paper 6, Further work item 1, §M.1; Paper 3, §C.11.

51 The longitude record: landing strength or maria?

The body's own ejecta landed toward its trailing half (90°E) and met its leading half (90°W) head-on, so landings on the leading half were hard and those on the trailing half soft (Paper 6). Paper 6 finds toothed (irregular) rims 1.14–1.25 times more common at 90°W, but some of the intervals for the larger rims include zero, and part of the difference may come from the maria, which are not spread evenly between the two halves.

The question. How much of the 90°W / 90°E difference in rims, peaks and floors is landing strength, and how much is the maria?

What the model predicts. A hard landing on the leading half (90°W) and a soft one on the trailing half (90°E). Toothed rims are 1.14–1.25 times more common at 90°W, but some intervals of the larger rims include zero (Paper 6).

Data. The four caps of Paper 6, §N.1; the catalogue of lunar melt flows (Neish and co-workers).

Method. A manual audit of central peaks and rims; a join with the melt-flow catalogue; the same measures by crater age.

Where in the series. Paper 6, Further work item 5, §§F.1, I.1, Study 6 (orange); Paper 1, §D.1.

52 The trailing-side excess: the yield of craters from the openings near 90°E

The trailing half of the Moon has more large craters than the leading half: 1.96 times as many before the maria are masked, 1.45 times after. The model attributes the excess to the body's own ejecta, which landed toward the trailing half, and to the larger number of openings near 90°E. The link between the openings and the excess is a requirement; the number of craters the openings near 90°E produced has not been computed.

The question. Did the more numerous openings near 90°E make enough craters ≥ 20 km to explain the trailing-side excess (1.96 raw, 1.45 masked)?

What the model predicts. The body's own ejecta land toward the trailing half. The link is a requirement, not yet a result (Paper 6, Paper 7).

Data. Crater density as a function of distance from each mare.

Method. The ejection history of each opening, carried through the flights of Paper 6 to a landing yield.

Where in the series. Paper 7, Further work item 9, §§E.2, A.9; Paper 6, §K.4; Paper 1, §F.2, table of open computations ("the yield of craters from the openings about 90°E").

53 The Earth as the last scatterer

The last small craters on the smooth mare floors are more numerous on the near side, 1.12–1.27 times, with secondary craters (craters made by blocks thrown out of a larger crater) removed (Paper 5, Study 9, green). The model reads this as material from the Earth, the last scatterer facing the near side. The open step is to count those craters by distance from each candidate source, so that a near-side excess that remains after the distance is held fixed can be attributed to the Earth.

The question. Do the last small craters on the smooth floors increase away from the contact, with a near-side excess remaining once that increase is held fixed?

What the model predicts. The near-side excess of the last small craters is 1.12–1.27 with secondaries removed (Study 9, green). The open test is a count by distance from each candidate source (Paper 5, Paper 6).

Data. Fresh craters of 1–2 km; masks of rays and secondary fields.

Method. Counts on the floors by distance from each candidate source.

Where in the series. Paper 5, Further work item 3, §§F.6, M.3; Paper 6, §§L.7, O.1.

54 Material after release poorer in iron

After release the heavy material sank back down the pear toward the Earth and the light rose (Paper 3, §C.10); a gas-driven outflow drives the light and small pieces fastest, and to reach the Moon material had to leave the Earth at 8.8 km/s or more. What reached the Moon was therefore the lighter part. A crater made on a mare by such material should then throw out ejecta poorer in iron than the basalt around it. Among the craters within the basalt the present result stays inside the scatter of the maps, and depth of excavation, which brings up different layers, has to be held fixed.

The question. Are the ejecta of craters made on the maria after release poorer in iron than the mare around them, with excavation depth controlled?

What the model predicts. What reached the Moon from the Earth after release was the lighter part. Among craters within the basalt the result stays inside the scatter of the maps (Paper 6).

Data. FeO maps at higher resolution.

Method. Ejecta against the surrounding mare, by crater size and excavation depth.

Where in the series. Paper 6, §§L.6, O.1, Study 12 (orange); Paper 1, §D.1.

55 Iron of the high and low floors

Some crater floors on the maria froze high, others sank back. In the model a floor that froze high held its volatiles and lighter material, and should be poorer in iron than a floor that sank. Paper 6 finds the low floors richer, but measured against the basalt just outside each crater the difference (–0.44 against –0.64 wt% FeO) is not beyond chance.

The question. Are floors that froze high poorer in iron than floors that sank back?

What the model predicts. High floors held their volatiles and lighter material. Low floors are richer, but against the basalt just outside the difference (–0.44 against –0.64 wt%) is not beyond chance (Paper 6).

Data. FeO maps; floor heights relative to the basalt outside.

Method. A larger or higher-resolution sample.

Where in the series. Paper 6, §§G.3, O.1, Study 11 (orange); Paper 1, §D.1.

56 Crater-count ages against direct ages of the same surface

In the literature the age of a surface is read from the number of craters on it, and the count is turned into years by a calibration curve (the chronology of Neukum and co-workers) that assumes a known and steady rain of bodies from outside, anchored on the samples returned by Apollo and Luna. Paper 6 replaces that rain: in the model almost all the craters were made by returning material, whose rate rose and fell with

the activity of the openings and of the Earth. A count of craters then measures how much a surface received, not how long it stood open (Paper 6); where the surface received more than an outside rain would have given it in the same time, a count converted with the calibration reads it as older than it is. Where one surface has been dated both ways — by its craters from orbit and directly, by radioactive decay in a returned sample — the direct age should therefore come out younger, and systematically so. Chang'e-6 has given one such pair so far: crater counts of 2.98–1.54 Gyr for the western mare at the landing site, and a laboratory age of 2.807 ± 0.003 Gyr for about 99% of the basalt fragments (Paper 8, B9, B15). One pair, lying inside the counted range, cannot show a trend; the comparison over many surfaces has not been made.

The question. Where the same surface has been dated both by crater counting and directly, is the direct age systematically younger than the crater-count age?

What the model predicts. Yes. The craters came mostly from returning material at a rate that was not steady, so a count converted to years by a constant flux overstates the time of exposure (Paper 6, Part M). A direct age that is younger than the count supports the model. The model also reads a direct age as the time the material cooled and closed, the age of the surface, not of the opening beneath it (Paper 5, §K.1).

Data. Published crater-count model ages and radiometric ages of the same units: the Apollo and Luna sites, Chang'e-5 (about 2.0 Gyr) and Chang'e-6 (Paper 5, §K.1; Paper 8, B9).

Method. Pair each dated sample with the crater-count age of the unit it came from, counted on that unit alone. Since the calibration curve is anchored on the Apollo and Luna ages, those sites agree with it by construction; the test rests on surfaces outside the calibration set, using counts published before the sample was dated. The relative clocks of the series — superposition and crater density compared between surfaces — are kept as they are; only the conversion to years is tested.

Where in the series. Paper 6, Part M (Dating) and the row “The ages” of the comparison table in the front matter; Paper 5, §§K.1–K.2; Paper 8, B9 (table of ages) and B15. Related: topics 29 (the order of sealing) and 48 (the crater size distribution).

57 The rays of young craters: material within the surface

Rays are the bright streaks that run outward from some young craters, sometimes for hundreds of kilometres. In the accepted reading they are ejecta: material thrown out by the crater and laid on top of the ground around it. The author's proposal reads them differently: a ray is a record within the ground beneath the surface, not ejecta lying on it — material that met a cold, glassy surface and froze into it. A ray forms only where the material lands on a floor that has already cooled; on a floor that is still hot, no ray forms. This holds for the floors of the maria, and equally for the basalt plains of the near side — Oceanus Procellarum and the plains around it, where Copernicus, Kepler and Aristarchus lie — which, exposed to the great heat of the nearby Earth, are very similar to the mare floors. Copernicus, Kepler and Aristarchus landed after their floor had cooled, and they carry rays. Diophantus and Delisle landed while the floor was not yet fully frozen, and they carry none. On these floors a ray is therefore a mark of time: a rayed crater landed on a floor already cold, a crater without rays on a floor still warm.

The proposal differs from the accepted reading in three observable things. The first

is depth: a layer laid on top is thin, and small fresh craters inside a ray would cut through it to the darker ground beneath, while a ray frozen within the ground continues downward. Tycho, a large rayed crater in the southern highlands, is the test case: its rays cross highland ground and also reach the maria. The second is the state of the floor: on the mare floors and the basalt plains, rayed and rayless craters of the same size should be told apart by whether the floor had cooled when the material landed. Rayed craters as such are not confined to the near side: Paper 7 (§D.3) found the 61 rayed craters of Grier et al. about as dense on the far side as on the near (2.01 against 1.70), so the test must look at the rays themselves — where the streaks are seen, on which floor and how far they reach — and not only at the craters that carry them. The third is number: among the small and medium craters of the near side, those without rays should outnumber those with rays. The reason is the order of events: the floors cooled while the Moon receded, and as it receded less material reached it, so fewer craters landed on cooled floors than on warm ones. Neither reading has yet been tested on these terms.

The question. Are the rays of young craters a record frozen within the ground rather than ejecta lying on it, and do they form only where material landed on a floor that had already cooled?

What the model predicts. The rays lie within the ground, not on top of it. On the mare floors and the basalt plains, craters that landed after the floor cooled carry rays (Copernicus, Kepler, Aristarchus), and craters that landed while the floor was not yet fully frozen carry none (Diophantus, Delisle). Among the small and medium craters of the near side, those without rays outnumber those with rays, because less material landed as the Moon receded. Tycho, a rayed crater in the highlands, is the case on which the depth of the rays is tested.

Data. LROC images and the LROC mare map; Kaguya Multiband Imager maps of iron and of surface maturity; the rayed-crater lists of Grier et al. (2001) and of Werner and Medvedev (2010), the latter with 1,615 rayed craters (Paper 7, §§D.3, E.4); crater catalogues of the near side for the count of craters without rays.

Method. Map the extent of each ray system and divide it between mare and basalt-plain floors and highland ground, per unit area and by crater size, so that the comparison is like for like. On the mare floors and the basalt plains of the near side, count the small and medium craters with rays and without them, in the same size classes and on the same floors, and compare the two numbers. Along selected rays, and along the rays of Tycho in particular, read the floors and ejecta of small fresh craters inside the ray: dark material exposed from beneath a bright ray marks a thin layer on top; bright material continuing at depth marks a ray within the ground.

Where in the series. Not yet in the series as a topic; raised in the author's working notes (16.10.2026 collection; brought to the author's current reading on 17.10.2026). The series touches rays in Paper 5, §F.5 (the ray fields of 16 young craters removed, to five diameters, from both sides of the floor count); Paper 6, §L.6 (the rays of Copernicus at the Apollo 12 site); Paper 7, §D.3 (the rayed craters, uniform in longitude). Related: topics 50 (captured ejecta after release) and 58 (the young craters of the poles).

The poles

Paper 7 reads the crowding of old craters toward the lunar poles (a pole-to-equator density ratio of 1.20 ± 0.05 in the clean count) as a mark of the body's change of figure: the craters formed while the body was flattened by its spin, and when it rounded inward the polar surface contracted while the craters kept their size, so that they came closer together. Craters formed after the Moon was round should show no such crowding. This part collects the topics that test that sequence: the young craters, the figure of a body with a stiff shell, the tide on a body held by its base, the spacing, the tectonic marks of the shell, and the details inside the caps. They matter because the polar record is the model's evidence that the Moon was once flattened, and therefore that it rounded on the Earth's pear rather than forming round.

No.	Topic	Readiness
58	The young craters of the poles	Public data
59	The figure with strength and the two-layer relaxation	New modelling
60	The tide on a body held by its base	New modelling
61	The spacing of the polar craters	Public data
62	The marks of the shell	Public data
63	The innermost caps	New data
64	The shallower polar craters	Public data
65	The alignment of elongated craters at mid-latitudes	Public data
66	The polar yardstick: the onset of central peaks	Public data
67	Crater ellipticity, and poles against the limb belt	Public data

Most of the polar topics are counts and measurements on public catalogues. The two orange topics are the physics of the figure; the one blue topic waits for a catalogue that reaches smaller craters near the poles.

58 The young craters of the poles

This is the cleanest test of the polar reading. If the crowding came from the rounding, craters formed after the Moon was round must be spread evenly in latitude, with a pole-to-equator ratio of about 1.0; if they show the old population's 1.2, the crowding has another cause. The present samples of young craters give 0.92 and 1.12–1.16: consistent with the model, but too small to decide.

The question. In a dated sample of about 150 young craters in the caps (and about 300 in the band), is the pole-to-equator ratio about 1.0 or the old population's 1.2?

What the model predicts. Craters formed after the Moon was round are uniform in latitude (0.9–1.1). The present samples give 0.92 and 1.12–1.16, consistent but not decisive (Paper 7).

Data. Mazrouei et al. (2019), Table S1 (published version); the 1,615 rayed craters of Werner and Medvedev (2010); new dated samples.

Method. A clean count by latitude on a verified, larger sample.

Where in the series. Paper 7, §§D.3, E.3 (item 3), Further work item 2; Paper 1, §F.3, item 7; Paper 1, §D.1 (Paper 7 orange row).

59 The figure with strength and the two-layer relaxation

A Maclaurin figure is the flattened shape that a uniform, fully fluid body takes when it spins. It gives the largest flattening the body could have had, and therefore an upper bound on the polar crowding. A body with a stiff shell flattens less, and so narrows the prediction from below. The interior, with a viscosity (resistance to flow) of 10^{21} – 10^{22} Pa·s, and the shell, at about 10^{23} Pa·s, also relaxed at different rates, and the way they shared the contraction sets the strain left in the shell.

The question. How much of the fluid flattening did a body with a stiff shell take, and how did the interior (10^{21} – 10^{22} Pa·s) and the shell (10^{23} Pa·s) share the contraction?

What the model predicts. The fluid figure gives the upper bound; a stiff shell narrows the prediction from below. The strain in the shell is shortening at the poles and fracturing at the equator (Paper 7).

Data. The measured clean ratio, 1.20 ± 0.05 .

Method. A Maclaurin figure with strength; a two-layer visco-elastic relaxation (a model in which each layer responds first elastically and then by slow flow) along the attached stage.

Where in the series. Paper 7, Further work items 1 and 3, §§C.1–C.2, C.7; Paper 1, §F.2, table of open computations.

60 The tide on a body held by its base

While attached to the pear the body was stretched along the line to the Earth by the tide, as well as flattened by its spin. Paper 7 reads the crater density in caps of 30° about six points: the sub-Earth, leading, south-polar, anti-Earth, north-polar and trailing points. Paper 7 measures the order of the six axes, the dense crown of the far side and the ratio of the largest craters (1.84 ± 0.38), and requires that the crown of the dome did not contract as a free end would. The tidal figure that would give those numbers has not been computed.

The question. Does the tidal figure of a body held by its base give the six-axis order as a number, the dense crown of the far side, and the ratio of the largest craters (1.84 ± 0.38)?

What the model predicts. The body was stretched along the Earth line as well as flattened by its spin. The crown of the dome did not contract as a free end; this is a requirement, not derived (Paper 7).

Data. Crater densities on the six axes (Paper 7, §A.9); the anti-Earth point, 221 after the mask.

Method. The tidal figure and its relaxation as the body rose.

Where in the series. Paper 7, Further work item 6, §§E.2 (“The crown of the far side”), A.9, D.2; Paper 1, §F.2, table of open computations.

61 The spacing of the polar craters

The polar reading says that the craters kept their size while the surface between them contracted. A density count shows this indirectly. The direct measure is the distance from each crater to its nearest neighbour, taken by diameter class: if the gaps closed, the polar craters should sit closer together than equatorial craters of the same size.

The question. Did the gaps between polar craters close, measured directly as the distances to the nearest neighbour, by diameter?

What the model predicts. The craters kept their size while the surface between them contracted (Paper 7).

Data. The Robbins catalogue.

Method. Nearest-neighbour statistics, caps against the equatorial belt.

Where in the series. Paper 7, Further work item 7, §D.2.

62 The marks of the shell

A stiff shell that contracts at the poles is shortened there, and one that is stretched at the equator cracks. Shortening leaves lobate scarps (low, curved cliffs where the crust is pushed over itself) and wrinkle ridges; extension leaves graben (long troughs where a strip of crust has dropped between two faults). Their distribution in latitude, outside the maria, is a test independent of the craters.

The question. Are shortening structures concentrated toward the poles and extensional ones toward the equator, outside the maria?

What the model predicts. As the stiff shell of Paper 7, §C.7 requires; a test independent of the craters (Paper 7).

Data. Catalogues of lobate scarps, wrinkle ridges and graben.

Method. The latitude distribution of the structures.

Where in the series. Paper 7, Further work item 8, §C.7.

63 The innermost caps

The contraction should be greatest at the poles themselves, so the crowding should rise inside the last 10° of latitude. The present counts there are too small to show it: 86 craters in the north and 36 in the south. A catalogue that reaches below 20 km near the poles would give the numbers needed.

The question. How does the crowding change within 10° of each pole, where the contraction should be greatest?

What the model predicts. The excess is greatest at the poles. The present counts are too small (86 craters in the north, 36 in the south) (Paper 7).

Data. The next catalogue generation, below 20 km.

Method. Profiles inside 10° of each pole.

Where in the series. Paper 7, Further work item 10, §D.4.

64 The shallower polar craters

Polar craters of 20–100 km are shallower than equatorial ones: a depth-to-diameter ratio (d/D) of about 0.062 against 0.074. Two causes can give this. The shell may have shortened around the craters and pushed their floors up, or the polar craters may simply be older and more degraded. The series has not separated the two.

The question. Are the polar craters of 20–100 km shallower (d/D about 0.062 against 0.074) because the shell shortened around them, or because of later degradation?

What the model predicts. Not separated in the series (Paper 7).

Data. LOLA depths; degradation classes.

Method. A search for shortening structures around the craters, against ordinary degradation.

Where in the series. Paper 7, §E.2.

65 The alignment of elongated craters at mid-latitudes

Among the most elongated craters (ellipticity $e > 1.2$, the ratio of the long axis to the short) at 30° – 60° latitude, 45–51% are aligned north–south, against 20–25% elsewhere. The size of the effect is a tenth or less of what deformation together with the surface would produce, so the model does not derive it; it is measured. Before it is read physically it must be checked against low-sun illumination, which can make rims traced from images look elongated in the direction of the light.

The question. Is the north–south alignment of the most elongated craters ($e > 1.2$) at 30° – 60° (45–51% against 20–25%) real, or an effect of low-sun illumination?

What the model predicts. Its size is a tenth or less of what deformation with the surface would give. It is measured, not derived (Paper 7).

Data. Rim traces from images lit from different directions.

Method. An illumination check of the Robbins rims; a repeat on independently traced rims.

Where in the series. Paper 7, §§E.2, D.5.

66 The polar yardstick: the onset of central peaks

Craters above a certain diameter form a central peak; below it they are simple bowls. The diameter of that transition depends on gravity and on the strength of the target, not on later contraction of the surface. If the polar craters kept their size, as the model requires, the transition must lie at the same diameter at the poles as at the equator.

It is a yardstick carried by the craters themselves.

The question. Is the crater diameter at which central peaks appear the same at the poles as at the equator?

What the model predicts. The same transition diameter: the craters kept their size (Paper 7, §§D.2, D.5).

Data. A catalogue of craters with central peaks below 15 km.

Method. A count of craters with a central peak, by size, in the caps and in the band.

Where in the series. Paper 7, §D.5.

67 Two topics left outside the model: crater ellipticity, and the poles against the limb belt

Paper 7 examined two further questions and left each as a study in its own right, because each needs its own definitions of region and of shape. The first asks whether the contraction left any elongation in the craters. The second compares the polar caps not with the equator but with the limb belt of Paper 11, the zone that stood at the edge of the near side during the attached stage. Without its polar parts the limb belt holds about 149 craters per 10^6 km², against 219 in the caps.

The question. (a) Did the contraction leave any elongation in the craters? (b) How do the caps compare with the limb belt of Paper 11 rather than with the equator (about 149 against 219 per 10^6 km²)?

What the model predicts. Both were examined in Paper 7 and left as studies in their own right, with their own definitions of region and shape (Paper 7).

Data. The Robbins catalogue.

Method. Independent definitions and counts.

Where in the series. Paper 7, Further work item 4.

South Pole-Aitken

South Pole-Aitken (SPA) is the largest and oldest basin on the Moon, a broad depression on the far side. In the series it is not the scar of a blow from outside. Paper 8 (*South Pole-Aitken*) reads it as the far-side end of a heat path: while the Moon was attached to the tip of the pear, heat from the Earth's interior entered the body through two exits on the near side — Imbrium, the main exit (the *burner*), and Serenitatis, the secondary — crossed it, and came up beneath the thin far-side crust. There it raised a dome, compacted the column beneath it, closed its pores and erased part of its crater record. Paper 8 measured five records of that heat itself (Studies 1-5, all green) and weighed seventeen published anomalies. This part collects what remains open: the physics and the budgets of the heat path (topics 68-70), the tests of Paper 8 Part F that need new data or a new count (71-76), and the two limits that Paper 8 stated on its own studies (77-78). The topics matter to the model because SPA is where the near side and the far side are tied together by one cause; each topic either strengthens that tie or names the observation that would cut it.

The table lists the twelve topics of this part. The colour of the right-hand cell is the readiness of each topic: green can be done now on public data, orange needs new modelling, blue needs a mission, samples or new data.

#	Topic	Source	Readiness
68	A physical model of the heat axis and its energy budget	Paper 8 §G	New modelling
69	A redox budget for the reduced mantle beneath SPA	Paper 8 §G, B12	New modelling
70	The dynamic tests recomputed with the series' constants	Paper 8 §D	New modelling
71	The volatile and redox gradient across the basin	Paper 8 §F	New data
72	Shallow craters and the minimum of depth after the mare mask	Paper 8 §F	Public data
73	The null test for Serenitatis, and an out-of-sample test	Paper 8 §F	Public data
74	A large early mare in SPA, later buried	Paper 8 §F, B9	New modelling
75	The late spray of small fragments	Paper 8 §F, B1h	Public data
76	Two crater populations and higher rims on young craters	Paper 8 §F, B1k	Public data
77	A direct porosity inversion for SPA	Paper 8 §G.1, B6	Public data
78	The missing crust of SPA	Paper 8 §G.1, B4–B5	Public data
79	Vapour that evaporated metals in SPA, and where it went	Paper 8 B11	New data

Read down the right-hand column: the three topics that open the part are the physics of the path and need new models; the middle of the part is a block of tests that can be made today on public maps and images; the last two turn the stated limits of Paper 8 into measurements.

68 A physical model of the heat axis and its energy budget

Paper 8 places the heat path by the marks it left: two exits on the near side, a dome and a hot centre on the far side, all on one north–south line. What it does not yet give is the physics of the path itself. A heat source that worked for the whole attached stage — in the model about 600 Myr from the start of the bulge to the release at 3.873 Ga, and at least $\sim 10^7$ years, the bound used for the viscosity estimate — had to carry enough energy across the body to do the work that Studies 1, 2 and 5 measured. This topic asks for that energy account.

The question. Did the heat that crossed the attached body from the Imbrium and Serenitatis exits suffice to compact the column, close the pores and erase the craters of SPA?

What the model predicts. One long-lived heat source, the burner, working through the attached stage (Paper 8). The work it must have done is measured: a crater density in the centre of 0.51 of that just outside the rim (Study 1); a remainder of depth of 1.1–1.8 km at the centre, which corresponds to a column of 9–15 km that lost 12% of its voids (Study 2); and pores at 10 km depth closed to 2.9–4.4% at the centre (Study 5).

Data. The results of Studies 1, 2 and 5 of Paper 8; the geometry of the path (exits, dome, hot centre) from Paper 8 Part C.

Method. A model of heat transport along the path from the exits to the far-side crust, and of the energy delivered over the attached stage, compared with the energy needed for the measured compaction and erasure.

Where in the series. Paper 8 §G, Further work 1; Paper 1 §F.2 (open computations: the heat axis, its energy and its redox budget).

69 A redox budget for the reduced mantle beneath SPA

The oxygen fugacity of a melt measures how much free oxygen was available when it formed. It is given relative to a reference reaction, the iron-wüstite buffer (IW): ΔIW is the number of orders of magnitude above or below it, so a more negative value means a more reduced melt, poorer in oxygen. Basalt fragments returned by Chang'e-6 from inside SPA give $\Delta IW -1.93$, against -0.80 for the near side — a mantle beneath SPA markedly poorer in oxygen. The model reads this as the work of the same heat source: prolonged heat drives oxygen off, and metallic iron from the Earth's interior takes up what remains.

The question. How much heat and how much metallic iron are needed to lower the oxygen fugacity from $\Delta IW -0.80$ to -1.93 , and does this agree with the heat budget of topic 68?

What the model predicts. Oxygen driven off by heat and consumed by iron from the Earth's interior (Paper 8, B12). The heat and the iron that the budget requires should fall within what the heat path delivered.

Data. The Chang'e-6 basalt fragments (23 fragments, measured by two methods).

Method. A redox mass balance: the oxygen to be removed from the source region, the iron to consume it, and the heat to drive it, set against topic 68.

Where in the series. Paper 8 §G, Further work 2; Paper 8 B12.

70 The dynamic tests recomputed with the series' constants

Part D of Paper 8 asked whether the numbers allow material and heat to travel from the Earth's interior to the far side of the attached body: the velocity and transit time of the flow, the energy and the pressure, the potential barrier and its relief in a continuous body, the sign of the net force, and the exit angle. Those tests were made before the series fixed its constants. They are to be repeated with the constants the series now uses, so that every number in Paper 8 rests on the same state as Papers 3 and 4. The *corotation radius* is the distance at which a body moving in a free orbit keeps pace with the Earth's spin; it is set by the length of the day and the Earth's mass.

The question. With a day of 5.77 h, the corotation radius of that state and the parent mass of the series, what are the effective potential barrier and the base pressure for a body of the shape of Paper 3 (*LEF Mechanism in Practice*)?

What the model predicts. The recomputation is required by Paper 8 §D.3a. The model requires the barrier to be relieved in a continuous body and the base pressure to suffice to drive the flow.

Data. None new; a recomputation with the constants of Papers 3 and 4.

Method. Repeat the velocity, transit-time, energy, barrier, sign and exit-angle tests

of Paper 8 Part D with the series' constants.

Where in the series. Paper 8 §G, Further work 3, and §D.1–D.5; Paper 1 §F.2.

71 The volatile and redox gradient across the basin

If SPA was heated from a centre, the marks of heat should fade outward. Volatile elements — those that evaporate easily, such as water and the alkalis — are driven off most where the heat is strongest, and the loss of oxygen follows the same pattern. The Chang'e-6 samples, taken some 210 km from the crater minimum, already show a mantle that lost its volatiles to heating (Paper 8, B11). One sampling point cannot show a gradient; maps can.

The question. Are volatile loss and reduction strongest near the crater minimum (45.4°S, 197.9°E) and weaker toward the rim?

What the model predicts. A heated centre, with the signature fading outward along the same radial profile as the crater deficit (Paper 8 Part F, row 2).

Data. Thorium (Th), iron oxide (FeO) and hydroxyl (OH) from orbital maps, sampled at the minimum and in rings around it.

Method. Radial profiles on the same rings as the crater study of Paper 8 (Study 1), with the same masks.

Where in the series. Paper 8 Part F, row 2, and “Tests that need new data”.

72 Shallow craters and the spatial minimum of depth after the mare mask

Study 1 found that craters of 40–80 km in the central 20° of SPA are 18% shallower than those of the rim belt. Two causes can make a crater shallow: heat from below that compacted and lifted its floor, or lava that later filled it. The model reads it as the first. The two can be separated by place: lava fill is found where lava is, under the visible maria and under *cryptomaria* — lava plains hidden beneath a later cover of material, recognised by the dark material that small craters dig up through the cover.

The question. Do shallow craters persist outside the buried basalts, and where are craters shallowest once the maria and their halos are removed?

What the model predicts. The shallowing comes from the burner, not from lava fill (Paper 8). Shallow craters should remain where there is no lava, and the minimum of depth should lie with the crater minimum (Part F, row 3).

Data. Crater depths from the Lunar Orbiter Laser Altimeter (LOLA); maps of maria and cryptomaria.

Method. Maps of crater depth with the mare mask (the maria, the cryptomaria and a halo around each removed), and the place of the minimum of depth.

Where in the series. Paper 8 Part F, row 3, and “Tests that need new data”.

73 The null test for Serenitatis, and an out-of-sample test

The crater minimum of SPA lies on the meridian of the point opposite Serenitatis (197.9° against 198.8°). The *antipode* of a point is the point on the opposite side of the sphere. A reader may object that the near side has many openings, and that one of their antipodes was bound to lie near the deficit. This topic answers the objection by measurement, in two ways: by asking how often chance alone gives such an agreement, and by testing the reading on data that were not used to build it.

The question. Would a deficit placed as well toward an antipode arise by chance for any opening? Does the reading hold on data not used to build it?

What the model predicts. The deficit follows the antipodes of the near-side openings, Imbrium and Serenitatis (Paper 8). Among all openings, the agreement should be rare by chance. A deficit with no relation to the antipodes of the near-side openings would leave the burner without its place (Part F, row 6).

Data. The catalogue of openings (Paper 5, *The Maria*, Appendix A); published crater catalogues.

Method. A permutation over all openings: compute the antipode of each, measure how well the deficit is placed toward it, and find the rank of Serenitatis. Then a held-out test on a crater catalogue or a size range not used in Study 1.

Where in the series. Paper 8 Part F, row 6, and “Tests that need new data”.

74 A large early mare in SPA, later buried

Inside SPA the visible maria are small patches. The model reads them as the tops of a larger early mare — an opening that once poured basalt over a wide part of the basin, then closed, and was covered by material that landed later. If so, the buried basalt should extend well beyond the visible patches, and its weight should appear in the gravity field. The *Bouguer gravity* is the gravity field after the attraction of the visible topography is removed; what remains shows dense or light material beneath the surface.

The question. Do the buried basalts extend well beyond the visible patches, and does the gravity field show the load of a buried basalt fill?

What the model predicts. A large early mare, closed and buried (Paper 8, B9, A.5). If the buried basalts end at the visible patches and the gravity field shows no buried fill, there was no large early mare (Part F, row 7).

Data. Dark-halo craters (small craters that excavate dark basalt through a lighter cover); spectra from the Moon Mineralogy Mapper (M³); GRAIL Bouguer gravity.

Method. A map of buried basalts from dark-halo craters and spectra; a gravity model of the basalt fill, its thickness and its extent.

Where in the series. Paper 8 Part F, row 7; B9; A.5.

75 The late spray of small fragments

In the model the late stages of the attached body threw out not large masses but a spray of small fragments. On the far side the rotation pulled outward: as a spinning

wet wheel throws off drops, not buckets, it stripped small, weakly held fragments from the surface, and these returned and landed as small, fresh craters on top of the older, large ones. The first test is made: inside SPA the ratio of small to large craters is 4.62, against 2.13 elsewhere (B1h). The second is prepared and frozen, so that its result cannot be shaped after the fact.

The question. Are the small craters on large hosts inside SPA fresh while their hosts are degraded?

What the model predicts. A late spray of small fragments (Paper 8). The second test is set: 20 host craters of 40–80 km inside SPA and 20 in a control at the same latitudes, frozen before inspection, with 2,634 candidate small craters, classified by fixed criteria and graded on a fixed freshness scale (depth relative to fresh craters of the same size; Krüger et al. 2018). The test is Part F, row 8.

Data. Images of the Lunar Reconnaissance Orbiter Narrow Angle Camera (LROC NAC).

Method. Inspection of each crater with the fixed criteria, recorded before any comparison between SPA and the control.

Where in the series. Paper 8 Part F, row 8; B1h.

76 Two crater populations and higher rims on young craters inside SPA

The history of SPA in the model has two parts: an old crater record erased in part by heat, and young craters that formed after the heat had compacted the ground. A crater formed on a compacted target — material whose pores have closed — keeps a higher rim than one formed on porous ground, which absorbs part of the excavation into compaction. Study 1 already found craters of 40–80 km in the centre with rims higher than in a matched control (B1k); this topic separates the craters by age.

The question. Are the old craters degraded and the young ones fresh, and do young craters inside SPA have higher rims than matched young craters outside?

What the model predicts. Two populations of different age, and young craters formed on a compacted target (Paper 8). A single population, or no difference in rims, would remove that history (Part F, rows 9–10).

Data. Crater ages (degradation class or counts on ejecta) and rim heights from LOLA.

Method. A matched comparison, inside and outside SPA, by age and by size.

Where in the series. Paper 8 Part F, rows 9–10; B1k.

77 A direct porosity inversion for SPA

Study 5 found the pores of SPA closed at depth, most at the centre. Its values were extrapolated from published inversions of the gravity field, which estimate how density and porosity change with depth from the relation between gravity and topography. Paper 8 named this as the limit of the study: the values depend on the depth model chosen. A direct inversion, made for SPA itself, removes that limit.

The question. Does an inversion made for SPA itself confirm pores nearly closed at 10 km, most at the centre?

What the model predicts. At 10 km depth, porosity of 2.9–4.4% at the centre, rising to 7.1–8.8% at the rim, against 6.2–12.8% around; at the surface, SPA as porous as the far side around it (Paper 8, B6). The heat came from below and compacted the deep layers, while the surface was renewed by material that landed later.

Data. GRAIL gravity; LOLA topography.

Method. A regional inversion of density and porosity with depth, on rings centred on the basin.

Where in the series. Paper 8 §G.1 (the limit of Study 5); B6.

78 The missing crust of SPA

The crust of SPA is thin, and the crust missing from the basin must be somewhere. In the model it slid off the rising dome and piled at the margins. Study 3 found that pile as an outer ring of thickened crust, 3.8–5.7 km at 50–55° from the centre, in seven of eight directions, thick to the east and missing to the west. That ring holds only about 37% of the missing crust. Study 4 found an inner ring that holds part of the rest on the west. The account is not yet closed.

The question. Where is the rest of the crust missing from SPA, given that the outer ring holds about 37% of it?

What the model predicts. The crust slid off the rising dome and piled at the margins; part of it lies in the inner ring on the west (Paper 8, B4, B5). The volume of the thinned basin should be matched by the two rings together with the regional trend of the far side.

Data. The four GRAIL crustal models.

Method. A volume balance: the crust missing from the thinned basin against the volume in the outer ring, the inner ring and the regional trend.

Where in the series. Paper 8 §G.1 (the limit of Study 3); B4; B5.

79 Vapour that evaporated metals in SPA, and where the vapour went

Paper 8 (B11) found that the heat beneath SPA drove off volatile elements: the ratio of potassium to thorium is low and flat across the whole heated region (451–455 within 30° of the centre, 16%–20% below the far-side highlands at 563 and the rest of the far side at 537), and in the Chang’e-6 basalts both potassium and iron are isotopically heavy — $\delta^{41}\text{K}$ of 0 to +0.09‰ and $\delta^{56}\text{Fe}$ of 0.13–0.21‰, against –0.29 to –0.04‰ and 0–0.11‰ in the near-side basalts of Apollo and Chang’e-5. Iron evaporates only under strong heat. The author’s proposal adds a carrier: a water-rich magma, cooked by the burner for a long time, released hot vapour in large amounts, and hot water vapour raises the evaporation of metals, which leave as compounds with water or chlorine at a lower temperature than in a vacuum. This would explain how iron too lost its light atoms. If it is right, the other metals that become more volatile in vapour — sodium, zinc and copper — should be depleted together with potassium and iron and be isotopically heavy as well, chlorine should be heavy, and the mantle source should be very dry. Paper 8 records an unusual drying (B11, B12), its source still to be cited, and leaves open where the vapour went: to space through the opening, recondensed at the margins of the basin, or both, and how much was lost. The other metals and

the vapour budget have not yet been measured.

The question. Is the mantle source beneath SPA very dry, and are zinc, copper, sodium and chlorine depleted and isotopically heavy together with potassium and iron? Where did the vapour go: to space, or did it condense at the margins?

What the model predicts. Prolonged heating of a water-rich source made hot vapour that carried off metals. The source is very dry; potassium, sodium, zinc, copper and iron are depleted together and isotopically heavy; chlorine is isotopically heavy. Potassium and iron are measured (Paper 8, B11); the other elements are the prediction of this topic. Vapour that recondensed at the margins would leave there the light isotopes that the centre lost.

Data. Chang'e-6 samples: the water content of the mantle source, and the isotopes of K, Fe, Zn, Cu and Cl, against the Apollo and Chang'e-5 basalts; the sodium and potassium recondensed in the Chang'e-6 glasses (Li et al. 2026); the potassium-to-thorium ratio at the rim (567 at the margin; Paper 8, B11).

Method. Measure the volatile metals and chlorine in the Chang'e-6 basalts as one set, so that a common depletion with heavy isotopes can be told apart from mixing of materials (the joint mixing model of K, Th, FeO and mineralogy named in Paper 8, B11). For the fate of the vapour, compare the isotopes of the condensed phases with those of the residue, and look at the margins for the excess of volatiles and of light isotopes that recondensed vapour would leave; the balance between centre and margins gives how much left the body.

Where in the series. Paper 8, B11 ("Open": where the vapours went and how much was lost), B12 (the dry mantle), and B6 (the voids opened by escaping gas). Related: topics 68 (the heat axis and its energy budget), 69 (a redox budget for the reduced mantle beneath SPA) and 71 (the volatile and redox gradient across the basin).

RESULT

Part G in brief. The heat path of Paper 8 is placed by its marks and measured in five studies; what is open is its physics (topics 68–70), the remaining tests of Paper 8 Part F (71–76), and the two stated limits (77–78); topic 79 asks what else the vapour carried off, and where it went. Six of the twelve topics can be done now on public data.

The stripes and the Pacific

The floor of the North Pacific is crossed by long, straight, parallel stripes that run east-west for thousands of kilometres, from Mendocino in the north to Clipperton in the south. Paper 9 (*The Stripes*) reads them as the leading side of the pear on which the Moon was built. The pear stood on the Pacific with its base near Kiritimati (1.9°N, 157.5°W) and leaned back against the Earth's rotation, its tip lagging to the west. Its front, the *leading side*, facing the rotation, was stretched while the pear stood and folded into stripes when the pear fell back into the Earth; its back, the *trailing side*, crumpled into the arcs of the western Pacific. Paper 9 named nine studies that would turn its readings into measurements (topics 80–88). Two further topics concern the deep Earth and the region as a whole: the Pacific low-velocity province as the returned pear (89), and a reconstruction of the Pacific lithosphere made without the lunar map (90). These topics matter to the model because the Pacific is the Earth's side of the separation: if the pear stood there, it left marks there.

The names on the map (Mendocino, Murray, Molokai, Clarion, Clipperton and others) are used here as names of places only. The topics of this part read the stripes as the series reads them, as the folded leading side of the pear; they do not take up any other reading.

#	Topic	Source	Readiness
80	Study 1 — the equator refitted on full traces	Paper 9 §G	Public data
81	Study 2 — the chance test of the base on the equator	Paper 9 §G	Public data
82	Study 3 — the stripes on one side only	Paper 9 §G	Public data
83	Study 4 — steps in depth and age across each stripe	Paper 9 §G	Public data
84	Study 5 — the trailing side	Paper 9 §G	Public data
85	Study 6 — continuity beneath the ridges	Paper 9 §G	Public data
86	Study 7 — the spatula ridges against ridges built from below	Paper 9 §G	Public data
87	Study 8 — the mirror imprint	Paper 9 §G	Public data
88	Study 9 — the stripes beneath the dated layers	Paper 9 §G	Public data
89	The Pacific province as the returned pear (R10, R11)	Papers 3, 11	New data
90	An independent reconstruction of the Pacific lithosphere	Paper 11	New modelling

The table shows the character of this part: the nine studies of Paper 9 can all be made now, on bathymetry, gravity, age grids and drilling records that are public. The isotope survey of topic 89 needs new samples of plume basalts, and topic 90 a new reconstruction.

80 Stripes Study 1 — the equator refitted on full traces

Each stripe lies along a *small circle* — a circle on the sphere drawn at a fixed angle from a pole, as a line of latitude is drawn about the Earth's pole. Parallel stripes on small circles about one pole define an equator of their own, the *equator of the stripe system*. Paper 9 found that equator tilted to today's equator: the first fit gives 11° , crossing today's equator at 159°W ; refitted on the author's own points the inclination is at least 10° , up to about 20° . The base of the pear lies on it. The exact value, with its errors, is this topic.

The question. What is the inclination of the equator of the stripes, and where does it cross today's equator, with errors?

What the model predicts. One equator, inclined at least 10° (first fit 11° , up to about 20°), passing through the base of the pear (Paper 9).

Data. Bathymetry (GEBCO); traces of the full stripes drawn on it.

Method. A fit of small circles about a common pole to the authors' own traces of the full length of each stripe, with errors from the scatter of the points.

Where in the series. Paper 9 §G, Study 1, and §E.1–E.3; Paper 1 §F.3, item 6.

81 Stripes Study 2 — the chance test of the base on the equator

The base of the pear near Kiritimati lies 1.6° from the equator of the stripe system. Any point has some chance of lying close to a given line, so the agreement means something only if it is rare. This topic measures how rare.

The question. How often does a point placed at random in the region fall within $\pm 2^\circ$ of the equator of the system?

What the model predicts. The base lies on the equator of the system, 1.6° from it (Paper 9, B.2). If that position is rare by chance, it is a meaningful agreement; if it is common, it is not.

Data. As in topic 80.

Method. A Monte Carlo test: many random points over the region, and the fraction that fall within $\pm 2^\circ$ of the fitted equator, repeated over the range of fits of topic 80.

Where in the series. Paper 9 §G, Study 2; §B.2.

82 Stripes Study 3 — the stripes on one side only

A pear that leaned back against the rotation had two different sides: a front that was stretched and a back that lay beneath the leaning tip. Its marks should differ accordingly. The stripes should begin in the region of the base and run east, on the leading side; what lies west of the base should be something else — the bending and converging of the floor and the crumpled back of the pear.

The question. Do the stripes begin at the base and run east, and is what lies west of it bending and crumpling rather than the same stripes continuing?

What the model predicts. The stripes are the leading side of the pear (Paper 9, B.3, B.6).

Data. Bathymetry; maps of magnetic anomalies of the sea floor.

Method. Tracing of each stripe westward from the base, recording where it ends, bends or converges.

Where in the series. Paper 9 §G, Study 3; §B.3, B.6.

83 Stripes Study 4 — steps in depth and age across each stripe

Across each stripe the floor may change in a step, in depth and in the dated age of its surface. If the stripes are folds of one structure, the leading side of the pair, those steps should not be random; they should be ordered about the base, growing toward it or away from it.

The question. Does the sea floor change in steps of depth and age across each stripe, ordered about the base?

What the model predicts. An order about the base, which ties each stripe, one by one, to the pair (Paper 9).

Data. Bathymetry; grids of the age of the sea floor.

Method. Profiles across each stripe; the step in depth and in age read on each, and plotted against distance from the base.

Where in the series. Paper 9 §G, Study 4.

84 Stripes Study 5 — the trailing side

The back of the pair lay beneath its leaning tip, to the west of the base. When the pair fell back, that side did not stretch; it collapsed and crumpled. Paper 9 reads the arcs of the western Pacific as that collapse, at 8,100–10,300 km from the base — a first reading, marked orange in Paper 9 §H.

The question. Is the Pacific asymmetric east-west about the base, with parallel stripes on the leading side and crumpled arcs on the trailing side?

What the model predicts. The back of the pair collapsed into the arcs of the western Pacific, 8,100–10,300 km from the base (Paper 9, B.8).

Data. Bathymetry; the geometry of the arcs.

Method. An east-west comparison about the base: the shape, spacing and orientation of the structures on each side, measured at matched distances.

Where in the series. Paper 9 §G, Study 5; §B.8; §H; Paper 1 §D.1.

85 Stripes Study 6 — continuity beneath the ridges

The Pacific floor is crossed not only by the stripes but by chains of seamounts and ridges that run across them. Which came first? If the stripes are an older fold of the leading side, they should pass beneath the ridges unbroken, on the same circle on both sides. Paper 9 observed four such crossings. It also proposed a test of order: if a fold formed under a standing ridge, the ground under the ridge was drawn together, and the ridge should be shortened, crowded or bent where the fold passed beneath it; if the ridge is untouched, it came later. The convergence of the stripes west of

the ridges is a first reading on oblique views (orange in Paper 9 §H); oblique views exaggerate height and distort distance, so the measurement must be made on a flat map.

The question. Does each stripe continue on the same circle on both sides of a ridge, and is the ridge shortened where the fold passed beneath it?

What the model predicts. The stripes pass beneath the ridges (four crossings observed) (Paper 9, B.5–B.6, F.2).

Data. Bathymetry.

Method. A flat map without vertical exaggeration, with the coordinates of each stripe read from the cursor on both sides of each ridge; the length of each ridge measured where a stripe crosses it.

Where in the series. Paper 9 §G, Study 6; §B.5–B.6, F.2; Paper 1 §D.1.

86 Stripes Study 7 — the spatula ridges against ridges built from below

Lift a spatula from wet plaster and the plaster is drawn up into ridges behind it. Paper 9 reads three Pacific chains — the Line Islands, the Marshall–Gilbert–Tuvalu chain and the Hawaiian–Emperor chain — in this way: drawn up from above by the lifted tip, spaced as the tip was wide, 2,800–3,500 km apart. Elsewhere in the world there are ridges that the literature reads as built from below, by a source of heat rising beneath the floor: Ninetyeast, Walvis and Chagos–Laccadive. A chain built from below over a fixed source shows a *plume age progression*: the ages of its volcanoes increase steadily along its length. The Line and Marshall chains show no such progression. Hawaii–Emperor does show one, from 0 Ma at Hawaii to about 81 Ma at the far end of the Emperor chain; the model requires that, on a spatula ridge, such a progression be a later sequence of eruptions on a ridge that already stood.

The question. Do the Line, Marshall–Gilbert–Tuvalu and Hawaiian–Emperor chains differ from Ninetyeast, Walvis and Chagos–Laccadive in age, shape, flexural moat, crustal root and orientation? How does the Hawaiian age progression fit?

What the model predicts. The chains were drawn up from above by the lifted tip, spaced as the tip was wide (2,800–3,500 km). Line and Marshall show no plume age progression (Paper 9, D.1–D.4, F.3; the comparison is orange in §H). A *flexural moat* is the trough that forms around a load as it bends the floor beneath it, and a *crustal root* is the thickened crust beneath it; a ridge built from below and a ridge drawn up from above should differ in both.

Data. Radiometric ages; gravity and flexure data; seismic measurements of crustal roots.

Method. A side-by-side comparison of the six chains on the five measures; the Hawaiian ages examined as eruptions on a standing ridge.

Where in the series. Paper 9 §G, Study 7; §D.1–D.4, F.3; Paper 1 §D.1.

87 Stripes Study 8 — the mirror imprint

When the Moon sat on the tip of the pear, its near side faced the Earth. The two faces stood facing each other, so the near side should have left an imprint on the floor

beneath it as a mirror image — as with a seal pressed into wax, east and west are exchanged while north stays north. The imprint should also be larger than the near side is today, by 1.37: the Moon then had a density of $1,300 \text{ kg m}^{-3}$ against 3,344 today, and the same mass packed into a smaller volume makes every distance on its surface shorter by that factor. With Imbrium in place (13.19°N , 179.04°E), the mirror predicts Serenitatis near 11.5°N , 166.3°E and the contact centre near 8.2°N , 179.3°W .

The question. Are circular features found on the floor at the mirrored places of Serenitatis, Nectaris, the contact centre and the other near-side maria, at the scale 1.37?

What the model predicts. A mirror image of the near side, with Imbrium in place (Paper 9, C.3).

Data. Bathymetry; gravity.

Method. The predicted positions of every near-side mare marked on the map before inspection, then inspected for circular features against random control positions.

Where in the series. Paper 9 §G, Study 8; §C.3.

88 Stripes Study 9 — the stripes beneath the dated layers

The sea floor of the Pacific is dated at most about 180 Myr, while the pear fell back at the release, 3.873 Ga. The model reconciles the two by depth: the dated sea floor is the last layer laid on an older fold. The stripes are then a structure of the layer beneath the dated surface, a relief that the new layers have draped rather than created. This reading is a first reading (orange in Paper 9 §H). It is tested where the stripes are crossed by *seismic reflection profiles* — sections of the floor made by sending sound waves down and recording their echoes from the layers below — and by drill holes.

The question. Does the fold continue below the youngest layers, with thinner layers over its crests and thicker layers in its troughs?

What the model predicts. The dated sea floor (at most about 180 Myr) is the last layer laid on an older fold (Paper 9, F.1).

Data. Seismic reflection profiles; drill holes of the Deep Sea Drilling Project and its successors (DSDP, ODP, IODP).

Method. The thickness of each layer measured across the fold, on profiles and holes that cross a stripe.

Where in the series. Paper 9 §G, Study 9; §F.1; §H; Paper 1 §D.1.

89 The Pacific province as the returned pear (R10, R11)

When the Moon left the tip, the rest of the pear — about nine lunar masses, seven to twelve in the range of Paper 9, some 11% of the Earth's mass — had nothing to hold it out and fell back whole. All of it lay inside the corotation radius, so none of it could stay in orbit (requirement R10 of Paper 11). Its heavy part sank to the base of the mantle beneath the base of the pear. We propose — with reservation, since the nature of the deep provinces is still open and the Pacific one may in part be core-related material that did not finish sorting — that this returned pile is the Pacific *large low-velocity province*: a region of continental size at the bottom of the mantle, just

above the core, through which seismic waves travel more slowly than through the mantle around it (R11). The African province, the second of the two, is read as the undisturbed lobe opposite. The position has passed: five of five tomographic models vote the point beneath Kiritimati slow, and it lies inside the -1% contour of SMEAN and SMEAN2, averages of several shear-wave models, at 2,800 km depth. What remains is composition, shape and the isotopes of the plumes that rise from it. Seismic waves slow down both in hotter material and in material of different composition, so the test must reach beyond velocity.

The question. Is the Pacific province richer in iron, denser, lower and broader than the African one? Is its northern part the base of the pear? How is it related to the Hawaiian ultra-low-velocity zone, a thin patch at the base of the mantle where waves slow far more than in the province around it? Do the plumes that rise from it carry only the Earth's signature?

What the model predicts. A returned, iron-rich pile beneath the base of the pear; about nine lunar masses (seven to twelve) returned whole, with no orbiting remnant (R10); the base over the northern part of the province, some 1,500 km north of its centre (Papers 3 and 11). Plumes from the province carry only the signature of the Earth.

Data. Tomographic models; constraints on density from the Earth's normal modes (the whole-Earth vibrations excited by great earthquakes); isotopes of plume basalts (He, W, Ne, Xe).

Method. A comparison of the two provinces in density and shape; an isotope survey of the plumes of the Pacific and of the African province.

Where in the series. Paper 3 §E.1–E.4; Paper 11 §C.5, C.6 (R10, R11); Paper 1 §F.3, item 5; Paper 1 §D.1 (the Paper 3 row awaiting).

90 An independent structural reconstruction of the Pacific lithosphere

The series places the source region on the Pacific by reading the Moon: the base near Kiritimati, the back of the pear near 25°N , 165°E , the tip at 9.3°N , 169.3°E , about 3,760 km west of the base. The *lithosphere* is the rigid outer shell of the Earth, the crust together with the cold top of the mantle. A reconstruction of the Pacific lithosphere made by others, from its own structure and magnetic record and without the lunar map, is an independent check: if it places the source region where the series reads it, the agreement does not come from the method.

The question. Does a reconstruction of the lithosphere beneath the Pacific, made without the lunar map, place the source region where the series reads it?

What the model predicts. The base near Kiritimati; the back of the pear near 25°N , 165°E ; the tip at 9.3°N , 169.3°E (Papers 3, 9 and 11).

Data. Published reconstructions of the Pacific lithosphere; palaeomagnetic data (the direction of the ancient magnetic field recorded in the floor).

Method. An independent reconstruction, made blind to the lunar map and compared with it afterwards.

Where in the series. Paper 11, Further work 7, and §C.2.

RESULT

Part H in brief. The nine studies of Paper 9 (topics 80–88) can all be made now on public bathymetry, gravity, age grids and drilling records; they fix the equator of the stripes, test the base against chance, and check the order of stripes, ridges and dated layers. The deep side of the account — the Pacific province as the returned pear, a reading held with reservation while the nature of the deep provinces is open — has passed its test of position and waits for composition and plume isotopes (89); an independent reconstruction of the region closes the part (90).

Mars and other bodies

Paper 10 follows the idea of the series on a second planet by another route. A young Mars, 1.5 times its present radius and turning once in five hours, fired two plugs of its own crust from one volcanic conduit at Pavonis Mons, pushed by trapped gas. A ring that Mars had built earlier from its own steam gave each plug the sideways speed it lacked, rounded its orbit and drew it into the equatorial plane, and the same friction ground it. The tide of the soft young Mars then pushed both moons outward: Deimos passed the final corotation line and recedes; Phobos was caught by the moving line and has been falling since. This part matters to the model because it is the one place where a moon made of its parent's interior can be tested on a second body, and because the Japanese MMX mission (Martian Moons eXploration) lands on Phobos in 2027, returns its samples in 2031 and passes close to Deimos. Several of the topics below are decided by that mission; the others are calculations or measurements that can be made now, so that the predictions are fixed before the samples arrive.

The table lists the sixteen topics of this part. The readiness column uses the three colours of the whole paper: green, the work can be done now on public data; orange, it needs new modelling; blue, it needs a mission, samples or new data.

No.	Topic	Readiness
91	The expanded, five-hour young Mars and the loss of its spin	New modelling
92	The gas push in a long conduit: the critical step	New modelling
93	The soft plug that seals: the cycle that builds it	New modelling
94	Drag in the conduit and the braking of Phobos	New modelling
95	The ring of condensed steam: mass, structure and coupling	New modelling
96	The tidal climb of Deimos and a soft young Mars	New modelling
97	The race of Phobos with the corotation line	New modelling
98	The samples of MMX: Martian material, one source, vesicles	New data
99	Pits and grooves on Phobos	Public data
100	The depth of the hollows on Deimos and Phobos	Public data
101	The centre of mass of Phobos	New data
102	The four calderas of Tharsis and the mass deficit beneath Pavonis	Public data
103	An ancient component in the Martian dust	New data
104	One conduit on the Martian equator, and the water beneath Tharsis (R18)	New data
105	The other bodies: Venus, Mercury and fast-spinning super-Earths	New modelling
106	The height difference between the poles and the spin at formation	New modelling

Most of this part is orange: Paper 10 computes the speeds, the energies and the orbits, and leaves the push in the conduit, the ring and the tidal history of a soft Mars as calculations to be made. Three topics can be started now on public shape models, images and topography; four wait for MMX and other missions. The last topic asks whether the height difference between a body's poles grows with its spin at formation.

91 The expanded, five-hour young Mars and the loss of its spin

Paper 10 takes the young Mars to have been 1.5 times its present radius, 5,084 km, with a five-hour day. At its equator anything leaving carried a free sideways speed of 1.78 km/s, the effective gravity was 1.04 m/s^2 , about a quarter of today's, and the corotation line stood at 7,057 km, less than 2,000 km above the ground. Such a planet holds about 12 times the spin of Mars today; to reach its present state it must have lost about 92% of it, mostly with volatiles that left through the corotation line.

The question. Can a self-consistent hot, volatile-rich young Mars have this radius and spin, and can it lose about 92% of its spin by shedding 5–20% of its mass through the line?

What the model predicts. A radius of about 1.5 times today's and a five-hour day; a loss of 5–20% of the starting mass, mostly volatiles, the lower value if the density rose toward the centre (Paper 10).

Data. Martian interior models, constrained by InSight; models of early volatile loss and of the deuterium enrichment of Martian water.

Method. A coupled model of the thermal contraction, the volatile loss and the spin of young Mars, with the angular momentum carried by mass leaving through the corotation line.

Where in the series. Paper 10 §B.1–B.4, §H.3, Part O item 1.

92 The gas push in a long conduit: the critical step

A free volcanic blast is limited to about 1 km/s. Paper 10 requires 2.4–2.9 km/s, and obtains it from trapped gas pushing a sealing plug along a confined path, as in a gas gun, whose limit is about 6.3 km/s. Along a path of 200–300 km the mean pressure needed is 0.25–0.47 GPa, comparable to the confining pressure of the surrounding material at that depth, 0.26–0.39 GPa, so the walls hold. The energy is 1.3×10^{22} J for Deimos and 3.6×10^{22} J for Phobos, with 10^{16} – 3×10^{16} kg of steam. Paper 10 names this as the critical step of its account.

The question. Can trapped gas in a deep chamber push a plug of crust along a conduit of 200–300 km to 2.4–2.9 km/s without breaching the walls or bypassing the plug?

What the model predicts. A mean driving pressure of 0.25–0.5 GPa, matched by the confining pressure along the path; a gas mass one to three times that of the plug (Paper 10).

Data. Rheology and strength of the Martian crust and mantle at depth; volatile contents of Martian magmas.

Method. A one-dimensional and then a two-dimensional model of a gas-driven plug in a deformable conduit, with gas expansion, wall stress and leakage past the plug computed together.

Where in the series. Paper 10 §C.3, §C.6, §C.8; Part O item 3.

93 The soft plug that seals: the cycle that builds it

In Paper 10 the plug is not a rigid block of rock but a warm body of high viscosity that seals the conduit as a rubber stopper does, a few kilometres below the vent. It is built by a Vulcanian cycle (Clarke et al. 2015, *The Encyclopedia of Volcanoes*, 2nd ed.): gas is released, the vent pauses, the plug cools and seals, mild pressure fails to open it, and gas accumulates beneath until it gives way. The impact marks on both moons, folded inward, are read as marks made on warm, plastic bodies.

The question. Over what range of viscosity and temperature does a plug of Martian crust seal a conduit against 0.25–0.5 GPa and then leave as one body rather than fragmenting?

What the model predicts. A soft, sealing plug that leaves whole; the first plug small, light and wet, the second larger, drier and harder (Paper 10).

Data. Viscosity and failure data for crystal-rich, volatile-bearing magmas; terrestrial Vulcanian sequences.

Method. A model of the cooling, sealing and failure of a viscous plug in a conduit, run through repeated cycles.

Where in the series. Paper 10 §C.4–C.5, §D.4.

94 Drag in the conduit and the braking of Phobos

A plug moving up a conduit on a spinning planet is pressed sideways by the Coriolis effect, $2\omega v \approx 1.8\text{--}2.0 \text{ m/s}^2$, against the western wall. Paper 10 reads the grooves of Phobos as the scrapes of that wall, and the braking of the second shot as the same contact. The first plug, Deimos, left without dragging.

The question. How much speed and how much mass does a plug lose against the wall of a conduit, and does the scoring concentrate on the side that faced west?

What the model predicts. Phobos braked to 2.4–2.6 km/s and lost about 1% of its mass; its grooves concentrated on the side that faced west (Paper 10).

Data. The groove maps of Phobos; the shape model.

Method. A contact and friction model of a viscous plug in a rotating conduit; a test of the orientation of the grooves against the predicted western side.

Where in the series. Paper 10 §C.7, §G.3, §K.1.

95 The ring of condensed steam: mass, structure and coupling

A plug fired from the surface reaches the height of the ring but not its orbit, and alone falls back within one revolution. In Paper 10 the missing speed comes from a ring that Mars built early from its own steam: a clear, hot gap near the planet, ice crystals and dust higher up, and clumps beyond about 13,000 km, the Roche limit for ice. To give a body its missing speed by perfect sharing of momentum the ring must hand over at least about 0.6 of the body's mass; real coupling needs several times that, of order 10^{16} kg. The account stands or falls with the ring.

The question. Can a young Mars build and keep such a ring, and does a body crossing it gain its orbit, round it and draw it into the equatorial plane before it is ground away?

What the model predicts. A ring of order 10^{16} kg; Deimos ground by 30–60% of its mass, mostly in the clumpy outer ring; Phobos, at the thin edge of a waning ring, by about 1% (Paper 10).

Data. Models of circumplanetary discs and of the early Martian atmosphere and water.

Method. An N-body or hydrodynamic simulation of a plug crossing a ring of condensed steam, with drag, erosion and the equatorial damping of the orbit.

Where in the series. Paper 10 §E.2, §F.1–F.3, §H.1; Part O item 4.

96 The tidal climb of Deimos and a soft young Mars

Beyond the corotation line the tide pushes a moon outward. Paper 10 carries Deimos from the ring, about 15,000 km, to its present 23,463 km, past today's line, 20,428 km, before the line arrived there. With the formula $da/dt = 3(k_2/Q)(m/M)(R/a)^5na$, this needs a young Mars dissipating 8 to 20 times more than today for half a billion to a billion years. Most of the time is spent in the outer part of the climb.

The question. What history of k_2/Q for a hot, soft, fast Mars carries Deimos to 23,463 km before the corotation line reaches 20,428 km, given its larger exit mass?

What the model predicts. A dissipation 8–20 times today’s for 0.5–1 Gyr (Paper 10).

Data. The present orbit of Deimos; models of the dissipation of a partly molten planet.

Method. A coupled integration of the spin of Mars, its dissipation and the orbit of Deimos.

Where in the series. Paper 10 §G.2, §J.1; Part O item 2.

97 The race of Phobos with the corotation line

Phobos was fired more weakly and reached only 10,000–11,000 km. Outside the line of its time, it was pushed outward by the tide, but the line moved outward faster as Mars slowed, and caught it near 19,000 km when the day was about 22 hours. From then Phobos lay inside the line and began to fall. Running its fall backwards at today’s dissipation, $k_2/Q = 1.816 \times 10^{-3}$, places it at 19,100–19,500 km 3.9–4.5 Gyr ago, consistent with Cheng et al. (2022, *Planet. Sci. J.* 3). Its inclination fell from 1.48° to the present 1.09°.

The question. Does one history of the spin of Mars and of its dissipation give both the outward push of Phobos and the faster outward motion of the line, so that the line catches Phobos near 19,000 km?

What the model predicts. The line catches Phobos near 19,000 km at a day of about 22 hours; inclination 1.48° to 1.09° (Paper 10).

Data. The present orbit and inclination of Phobos; the measured dissipation of Mars.

Method. The same coupled integration as topic 96, run for Phobos, with the inclination damping included.

Where in the series. Paper 10 §G.3, §K.4–K.5; Part O item 5.

98 The samples of MMX: Martian material, one source, vesicles

MMX will return more than 10 g of regolith from Phobos in 2031. In the model Phobos is Martian crust altered by water, from one source, never melted and re-condensed.

The question. Is Phobos Martian crust from one source, or a mixture of Mars and an impactor, or primitive asteroid material?

What the model predicts. Oxygen, chromium and titanium isotopes on the Martian line; no impactor component; zinc and potassium isotopes not shifted by evaporation; hydrated minerals; closed vesicles of a cooled foam (Paper 10, N.1).

Data. MMX samples (2031).

Method. Isotopic and textural analysis of the returned grains.

Where in the series. Paper 10 §N, Appendix B.

99 Pits and grooves on Phobos

In the model the grooves and the pit chains of Phobos are one structure, made in the conduit, and the grooves were etched by gas-borne dust, not smoothed by water.

The question. Do pits ever cross grooves? Are the groove walls V-shaped and the rims sharp or only slightly worn?

What the model predicts. Pits never cross grooves; V-shaped groove walls; sharp or slightly worn rims, unlike the rounded surface of Deimos (Paper 10, N.2).

Data. Existing images and shape models of Phobos; MMX imaging from 2027.

Method. Mapping of pit chains against grooves; profiles across groove walls and rims.

Where in the series. Paper 10 §K.1–K.3, §N.

100 The depth of the hollows on Deimos and Phobos

The shape models measured for Paper 10 (Ernst et al. 2023, *Earth, Planets and Space* 75) give a median depth-to-width ratio of the hollows of 1.9% on Deimos against 5.5% on Phobos: Deimos was worn far more. Both moons have a sharp end and a blunt end, the blunt end facing Mars.

The question. Does a full catalogue of hollows on both moons confirm the contrast, and does it show the rims of Deimos worn rather than buried?

What the model predicts. Shallow, worn hollows on Deimos; deeper ones on Phobos; low ridges on Deimos that are the roots of its tallest wrinkles (Paper 10, N.3).

Data. Public shape models of both moons; MMX flybys of Deimos.

Method. Automatic and manual measurement of the depth, width and rim profile of every hollow above a size threshold.

Where in the series. Paper 10 §J.1–J.2, §L.

101 The centre of mass of Phobos

A plug that cooled from its surface and was turned by the tide to face Mars with its blunt end need not be uniform.

The question. Is the centre of mass of Phobos displaced from the centre of its shape toward Mars, toward its blunt end?

What the model predicts. A displacement toward Mars and toward the blunt end; the accepted accounts give no prediction (Paper 10, N.5).

Data. MMX tracking close to Phobos.

Method. Gravity-field inversion compared with the shape model.

Where in the series. Paper 10 §N; Appendix B.

102 The four calderas of Tharsis and the mass deficit beneath Pavonis

The summit pit of Pavonis is a single circle 47 km wide and nearly 5 km deep, depth to width about 0.10, with a volume of 8,300–8,700 km³, of the scale of the two moons together, 6,740 km³. In the model it is the roof of a chamber that collapsed after the shots.

The question. Is Pavonis the deepest caldera for its width among the four Tharsis volcanoes, and is there a mass deficit beneath it?

What the model predicts. The deepest for its width (about 0.10); a mass deficit beneath it (Paper 10, N.4).

Data. MOLA topography; Martian gravity models.

Method. Depth and width of each caldera from MOLA; a local gravity inversion beneath each.

Where in the series. Paper 10 §I.1–I.3, §N.

103 An ancient component in the Martian dust

In the model the inner part of the ring fell back onto Mars as dust, mostly near the equator. Its grains spent time in space and should carry solar-wind gases.

The question. Does Martian dust contain a component older than 4 Gyr, with grains carrying solar-wind helium and neon and the composition of the Phobos regolith?

What the model predicts. Such a component, most abundant in the broad equatorial band and the dust continents (Tharsis, Arabia Terra, Elysium), mixed with rock ground by drought and wind (Paper 10, N.7).

Data. Returned Perseverance regolith samples; MMX samples of Phobos for comparison.

Method. Grain-by-grain dating and noble-gas analysis; comparison with Phobos.

Where in the series. Paper 10 §H.1, §N; Appendix B.

104 One conduit on the Martian equator, and the water beneath Tharsis (R18)

A body starts on an orbit tilted by the latitude of its launch site. Pavonis, at 1.48°N, is the closest of the four Tharsis volcanoes to the equator; Olympus, at 18.65°N, would have started a moon on an orbit tilted by about 19°. Both moons orbit within 2° of the equator. Requirement R18 of Paper 11 states that both were fired from this one conduit. The water that did not leave stayed sealed beneath the crust, where InSight found a water-saturated mid-crust.

The question. Are both moons Martian material from one equatorial conduit, and does a water-saturated mid-crust also lie beneath Tharsis?

What the model predicts. One source for both moons, Deimos the wetter; a water-saturated mid-crust beneath Tharsis as beneath InSight (Paper 10, N.5–N.6; Paper 11, R18).

Data. MMX samples and Deimos flybys; future seismic stations on Tharsis.

Method. Comparison of the composition of the two moons; seismic sounding of the Tharsis crust.

Where in the series. Paper 10 §D.1–D.4, §H.2, §M; Paper 11 §C.7 (R18).

105 The other bodies: Venus, Mercury and fast-spinning super-Earths

The mechanism needs fast spin: the corotation radius must lie close enough to the surface for the planet's own pressure to lift material to it. Venus turns once in 243 days and Mercury once in 59 days; their corotation radii lie far out, and nothing is lifted. Both have no moons, as the model expects. A massive, fast-spinning super-Earth is the opposite case. A parameter study over spin, mass and volatile content would turn this into a prediction for the moons of other planets.

The question. What does a parameter study in spin, mass and volatile content predict for the moons of other planets?

What the model predicts. Nothing is lifted on slow rotators (Venus, 243 d; Mercury, 59 d); more on a fast-spinning super-Earth (Paper 1).

Data. Satellite inventories of the planets; exoplanet spins and masses.

Method. The corotation and pressure tests of the series applied across the parameter space.

Where in the series. Paper 1 §F.3 item 9; Paper 10 §B (the part played by a fast spin).

106 The height difference between the two poles and the spin at formation

On Mars the two poles do not stand at the same height. The laser altimeter of Mars Global Surveyor (MOLA) shows the north polar region several kilometres lower than the south. The difference is part of the Martian dichotomy, the contrast between the low, smooth northern plains and the high, cratered southern uplands, and the literature has other explanations for it, among them a giant impact and a one-sided flow in the mantle. The author's proposal relates the difference to the spin: the faster the body turned when it formed, the larger the difference between its poles should be. In the series the speed of spin is what sets how close the corotation radius lies to the surface and how much material a young body can lift (Papers 2, 10); the topic asks whether the same quantity also leaves its mark on the heights of the poles. The hypothesis has not been tested.

The question. Does the height difference between the north and south poles of a body grow with the rate at which the body turned when it formed?

What the model predicts. The faster the spin at formation, the larger the difference between the poles. This is a hypothesis to be tested, not a result of the series.

Data. Polar topography from orbital altimetry: MOLA for Mars (Smith et al. 1999, *Science* 284), LOLA for the Moon, and the corresponding data for the other bodies with measured topography; the spin of young Mars from Paper 10 (§§B.1–B.2) and the spins of the series for the Earth and the Moon.

Method. First, a model step: spin alone flattens a body equally at both poles, so the calculation must name the one-sided element that turns a faster spin into a larger difference between the poles, and derive the relation from it. Second, a comparison: the difference between the poles measured on the ground beneath the polar ice caps, which on Mars are kilometres thick, relative to the equipotential surface of each body, and set against the spin at formation. On Mars the poles of today may not be those of

the time of formation, since a load as large as Tharsis can turn the planet beneath its spin axis; the comparison must allow for this.

Where in the series. Not yet in the series; raised in the author's working notes (16.10.2026 collection). Related: topics 104 (one conduit on the Martian equator, and Tharsis), 105 (the other bodies and fast-spinning super-Earths) and 115 (north-south asymmetry with South Pole-Aitken removed).

Requirements and key tests

Paper 11 sets the model against what it must satisfy: eighteen requirements (R1–R18), each matched with the measurement that tests it. This part collects the topics that remain open there. Two of them carry more weight than any other topic in this paper. The first is the geometry of exposure (topics 107 and 108): the Moon should be ordered in three zones about one centre on its near side, with the crust thinnest and the craters fewest where the contact with the Earth was exposed last. The second is the source of the craters (topic 109): in the model they were made by returning terrestrial material, not by bodies from outside. The remaining topics are the balances — isotopes, metal, crust, ages and volatiles — that the model must close with one set of numbers. Three topics close the part: what the lunar core is made of, whether the core is displaced toward the Earth, and whether the crust has a thin place that no basin and no opening explains.

No.	Topic	Readiness
107	T1 crustal thickness rerun on the current geometry, all four GRAIL models	Public data
108	The belt statistics completed: T2 by age, T3, T4, GRGM1200B	Public data
109	No foreign material: the isotopic decision (R14)	New data
110	A multi-system isotope balance (R1)	New modelling
111	The metal budget: the core as a gauge (R2, R13)	New modelling
112	The joint crust-centre-of-mass solution (R3, R7)	New modelling
113	Two crusts, two ages (R5)	New data
114	Volatiles in the amount and phase the feed needs (R6)	New modelling
115	North-south asymmetry with South Pole-Aitken removed	Public data
116	The composition of the lunar core	New data
117	The core offset as the residual of the centre-of-mass offset	New modelling
118	An orphan minimum of crustal thickness	Public data

The two exposure-zone topics are green: the data are public and the tests were fixed in advance, so they can be completed now. The isotopic decision waits for laboratory analyses of samples that already exist, and the composition of the core for new seismic and laboratory data; the core offset is a joint calculation, and the scan for an orphan minimum can be made now.

107 T1 crustal thickness rerun on the current geometry, all four GRAIL models

GRAIL, the twin spacecraft that mapped the Moon's gravity, gave four standard models of the thickness of the lunar crust (Models 1–4, differing in assumed density and porosity). The model requires the crust to be thinnest over the contact — the area joined to the Earth, exposed last — thicker in the belt around it, and thickest on the far side, whose surface was exposed from the start. Test T1 measures this ordering and the contrast far minus contact. The prediction is the ordering; the size of the contrast is a number for calibration. In September 2026 the test was run about the sub-Earth axis: the ordering held in all four models, with contrasts of 9.65, 10.0, 10.3 and 10.6 km. Paper 3 has since fixed the current geometry: the contact centre at 24.1°N 335.2°E, the cap 0–31°, the belt 31–70° and the far part 70–180°. On it, Model 1 gives 26.3, 30.3 and 36.2 km with the maria kept (contrast 9.9 km), and 31.3, 33.0 and 38.9 km with the maria and SPA removed (contrast 7.5 km). Models 2–4 have not been run on the current geometry. The author ruled on 15.10.2026 that this rerun is left to other researchers. The comparison must be like for like: whatever is masked (maria, SPA) is masked in every zone.

The question. With the full GRAIL grids for all four models, on the current geometry, does the ordering cap < belt < far hold, and how large is the far-minus-contact contrast, as a number for calibration?

What the model predicts. The crust thickens monotonically from cap to belt to far side. The ordering holds in all four models (rank correlation +0.87). The contrast on the September geometry is 9.65 / 10.0 / 10.3 / 10.6 km; on the current geometry Model 1 gives a contrast of 9.9 km (7.5 km with maria and SPA removed); Models 2–4 are left to the rerun (Paper 11).

Data. The four GRAIL crustal-thickness models (Wieczorek et al. 2013) at full resolution.

Method. Belt means by angular distance from the contact centre, with the zones fixed in advance, and the same mask applied in every zone.

Where in the series. Paper 11 §B.8, §B.9, Further work item 1, §D.3 (R8); Paper 1 §D.1, §E.2.

108 The belt statistics completed: T2 by age, T3, T4, GRGM1200B

T1 is one of five tests of the exposure zones fixed in Paper 11. T5, the thickness trend in twelve belts, passed with +0.87 in every model; T2, the density of craters of 20 km and more, passed (far/limb 1.34). Three steps remain. T2 should be repeated on the oldest craters selected by age (degradation class), since the record of exposure is held by them. T3 asks where the large ringed mascon basins lie (a mascon is a concentration of mass beneath a basin, seen in the gravity field); T4 asks the same of the strongest mascons without rings. Finally the ordering should be checked on gravity grids that do not depend on a crustal model: the Bouguer field (gravity with the pull of the topography removed), the lateral-density grids and the newer field GRGM1200B.

The question. Is the oldest crater population ordered by belt when selected by age? Are at least 60% of the ringed mascon basins at 41–105° (T3)? Are at least 70% of

the ten strongest unringed mascons within 50° (T4)? Does the ordering hold on the Bouguer and lateral-density grids?

What the model predicts. Three concentric zones about the near-side centre, and no other axis (Papers 3 and 11). T5 (+0.87) and T2 (1.34) passed; T3 and T4 have not been run.

Data. The Robbins (2019) crater catalogue with degradation classes; GRAIL gravity gradients; GRGM1200B.

Method. As in Paper 11 §B.8, with the thresholds fixed before the data are examined.

Where in the series. Paper 11 §B.8 (T2–T5), Further work item 1; Paper 3 §D.1; Paper 1 §F.3 item 1, §E.2, §D.1.

109 No foreign material: the isotopic decision (R14)

In the model about 99% of the lunar craters were made by returning terrestrial material: material raised from the Earth that came back down onto the Moon. The usual reading is the opposite, that the craters were made by asteroids and comets. The two readings differ in the material left behind. Elements formed in different parts of the early solar system carry different nucleosynthetic isotope patterns — small differences in the proportions of the isotopes of chromium, titanium, molybdenum, ruthenium and osmium, which act as a fingerprint of origin. Metal that was inside the ancient samples when they formed must carry the fingerprint of whatever made them. The model also makes a mass argument: if the visible craters were made by bodies from outside, the upper 5 km of the crust would have to hold $4.4\text{--}5.0 \times 10^{19}$ kg of foreign mass, 2–6%, whereas the measured content is 0.9–2% at most, and the ruthenium measured so far is terrestrial. Fine space dust in the regolith is allowed by the model; it is not the material of the craters.

The question. Does the metal that was part of the ancient samples when they formed — the iron–nickel of the two dated Chang’e-6 norites, and the siderophile elements (elements that follow iron) in the melts of each basin of the maria — carry a terrestrial or a non-terrestrial isotopic signature (Cr, Ti, Mo, Ru, Os)?

What the model predicts. About 99% of the craters are made of returned terrestrial material (Papers 1, 5, 6, 8, 11). The norite metal is terrestrial (Paper 8, B14, fits in part; the isotopes decide).

Data. The Chang’e-6 norites CE6C0100YJFM002-158 and CE6C0200YJFM001EGP07-16; melts from Apollo and Chang’e crater sites; Pacific plume basalts, as the terrestrial reference.

Method. Nucleosynthetic isotope analyses. A mixing model of a terrestrial returning body with a terrestrial target yields one pattern; asteroidal bodies, including differentiated ones, yield a second, foreign pattern. The source state is fixed before the measurements are compared.

Where in the series. Paper 8 B14, §E.1–E.2, Part F row 1, §G.2 item 8; Paper 5 §J.7, Further work item 4, §M.3; Paper 6 §L.5, Further work item 6, §O.1; Paper 11 §C.6 (R14), §D.3; Paper 1 §E.2, §F.3 item 4, §D.1.

110 A multi-system isotope balance (R1)

The Earth and the Moon are almost identical in their oxygen isotopes: $\Delta^{17}\text{O}$, the measure of the oxygen fingerprint, differs by -1 ± 5 ppm. For the model this is expected, since the Moon is made of terrestrial material. But oxygen is one system of several. The same starting composition — the shell of the early Earth plus the deep upwelling that fed the pear — must also give the lunar values of titanium, chromium, tungsten and the volatile elements once it has passed through separation and evaporation. A balance that closes in one system and fails in another would not support the model.

The question. Does one composition — early-Earth shell plus deep upwelling, passed through separation and evaporation — fit the lunar data in O, Ti, Cr, W and the volatile elements together?

What the model predicts. Terrestrial material throughout. Oxygen: $\Delta^{17}\text{O} = -1 \pm 5$ ppm between Earth and Moon (Paper 11).

Data. Published lunar and terrestrial isotope data.

Method. A multi-system mixing and fractionation model run with one set of inputs for all systems.

Where in the series. Paper 11, Further work item 2; §A.1, §B.1, §D.3; Paper 1 §E.1 (R1).

111 The metal budget: the core as a gauge (R2, R13)

The Moon's core is small: about 1.4% of its mass (range 1–2%), with a radius of about 330 km. In the model the material of the Moon rose from a source near the iron that was descending into the Earth's core, but not at it. A rising foamed melt entrains droplets of that iron; some settle out on the way, some are carried up. The size of the lunar core therefore measures how deep the feed reached. The topic is to compute the entrained fraction and see whether it gives 1.4%.

The question. What fraction of descending iron does a rising foamed melt entrain, and does it give a lunar core of about 1.4% (1–2%) from a source near, but not at, the descending iron?

What the model predicts. The small core measures how deep the feed reached (Papers 3 and 11).

Data. The seismic size of the core (about 1.4%); the feed rate of Paper 3.

Method. Fluid dynamics of droplet entrainment and settling in a rising melt.

Where in the series. Paper 11, Further work item 3; §A.2, §B.2, §C.6 (R13), §D.3; Paper 3 §C.10; Paper 1 §F.2.

112 The joint crust-centre-of-mass solution (R3, R7)

The Moon's centre of mass lies about 2 km from the centre of its figure, toward the Earth. In the model this offset, the thick far-side crust and the maria on the thin near side are one distribution of material seen in several ways. Paper 11 shows that a crust of the modelled shape displaces the centre of mass by 1.24–3.11 km for density contrasts of 300–750 kg/m³ — a sensitivity range, not yet a prediction — and that the

shell built on the dome of Paper 3, 2.85×10^{21} kg, matches the far-side crust, 2.6×10^{21} kg, to about 10% with no parameter adjusted between them. The topic is to replace the range with one density model that gives the size and the direction of the offset together with the measured thickness. Because R3 and R7 describe one distribution, they are tested once and not counted twice.

The question. Does one supported density model give the size and the direction of the 2-km offset of the centre of mass, together with the measured crustal thickness, on the exposure-zone geometry?

What the model predicts. 1.24–3.11 km for contrasts of 300–750 kg/m³, against about 2 km observed. Shell 2.85×10^{21} kg against far-side crust 2.6×10^{21} kg (Paper 11).

Data. GRAIL gravity; LOLA topography; the GRAIL crustal models.

Method. A joint inversion of crust and centre of mass.

Where in the series. Paper 11, Further work item 4; §B.3, §B.7, Appendix A, §D.3; Paper 3 §D.2; Paper 1 §F.2.

113 Two crusts, two ages (R5)

In the model the far side closed first: its surface was the outside of the dome from the start, and it was preserved while the near side was still joined to the Earth. The far-side highland crust should therefore be older than comparable near-side highland crust. The comparison must be made between like units, outside the basins, and with the same kind of clock: a crystallisation age is compared with a crystallisation age, not with the age of a later melt.

The question. Is the far-side highland crust older than comparable near-side highland crust, sampled outside the basins?

What the model predicts. The far side closed and was preserved first (Paper 11).

Data. Chang'e-6 material; future far-side samples.

Method. Crystallisation ages of comparable units on the two sides.

Where in the series. Paper 11, Further work item 5; §A.5, §B.5, §D.3.

114 Volatiles in the amount and phase the feed needs (R6)

Volatiles — water and other substances that become gas at low pressure — do two jobs in the model. Dissolved or as bubbles, they lower the density of the feed so that the column can stand to the corotation radius; and on expanding they supply its pressure. Lunar melt inclusions, small droplets of melt sealed in crystals, hold 615–1,410 ppm water, so the interior is not dry. What is still to be derived is the amount and the phase (dissolved or as gas) that the feed needed for density, flow and pressure at the same time.

The question. Does the measured water of lunar melt inclusions (615–1,410 ppm) correspond to the amount and phase that the density, the rheology and the pressure of the feed require at the same time?

What the model predicts. Volatiles lower the density of the feed and supply its pressure (Papers 3 and 11).

Data. Water in melt inclusions and in apatite.

Method. The transport requirement of topic 4 set against the measured inventory.

Where in the series. Paper 11 §A.6, §B.6, §D.3; Paper 3 §A.6.

115 North-south asymmetry with South Pole-Aitken removed

The Moon is clearly asymmetric between near and far side. Whether it is also asymmetric between north and south is not settled, and the answer is easily dominated by one feature: South Pole-Aitken, the largest basin on the Moon, lies entirely in the south. Any north-south difference that SPA alone produces says nothing about the rest of the body. The topic is to remove the near-far asymmetry and the large basins, SPA first of all, and see whether anything remains.

The question. Does any north-south asymmetry of the Moon remain once the near-far asymmetry and the large basins, SPA above all, are removed?

What the model predicts. To be examined, not assumed; SPA alone must not verify it (Paper 11).

Data. GRAIL crustal models; crater catalogues.

Method. An asymmetry analysis with SPA and the large basins masked in both hemispheres.

Where in the series. Paper 11 §C.5; Paper 7 §D.4.

116 The composition of the lunar core: the Earth's iron, caught on its way down

Topic 111 asks how large the lunar core should be; this topic asks what it is made of. Pure iron is not what planetary cores hold: some lighter element is always dissolved in the metal, and which element it is records how the core formed. Silicon and oxygen enter iron mainly when metal and silicate meet at the high pressures and temperatures of a deep, large core; sulphur enters at low pressure, as metal droplets settle through a silicate mantle. In the model the lunar core is the Earth's iron. When the pear grew, the Earth's iron was still descending toward its core; a large amount of it took part in the pear, most of it sank back to the Earth with the returning material, and the Moon kept what reached the tip (Paper 3, §C.10). That iron then gathered at the Moon's centre. The lunar core is therefore terrestrial metal, but metal caught on its way down: it had not yet joined the deep core and equilibrated at its pressures. Its light element should record that: the sulphur of metal that equilibrated at the shallower pressures of the descent, rather than the silicon and oxygen of metal equilibrated at the base of a large core.

The question. Is the light element of the lunar core sulphur, rather than silicon and oxygen?

What the model predicts. The lunar core is terrestrial iron, carried up with the feed while the Earth's iron was still descending (Paper 3, §C.10); its light element is mainly sulphur. A core whose light elements are mainly silicon and oxygen, as in metal equilibrated at the base of a large core, does not support this reading.

Data. The seismic core of Weber et al. (2011), radius about 330 km with a solid inner

core of about 240 km, and its density and wave speeds; new seismic data from a future lunar geophysical network; laboratory measurements of the density and sound speed of iron-sulphur and iron-silicon-oxygen liquids at lunar core pressures.

Method. The measured density and wave speeds of the outer core compared with those of the candidate alloys at lunar conditions; a model of the light-element content of the Earth's metal during its descent, carried to the tip and gathered at the Moon's centre.

Where in the series. The composition of the core is not yet in the series; it is raised in the author's working notes (16.10.2026 collection). The core as a gauge of the feed: Paper 3 §C.10; Paper 11 §A.2, §B.2 and §C.6 (R2, R13); topic 111.

117 The core offset as the residual of the centre-of-mass offset

The Moon's centre of mass lies about 2 km from the centre of its figure, toward the Earth. Paper 11 explains it by the crust: a light crust thickened on the far side moves the balance point toward the near side, by 1.24–3.11 km for density contrasts of 300–750 kg/m³ in its example, and it assumes a symmetric core that adds nothing in this direction. Topic 112 asks for one density model of crust and centre of mass together. This topic adds a separate term. The author's proposal is that the core itself is off-centre: the burner pushed it beyond the geometric centre of the Moon; before it had fully cooled it moved back toward the centre; and the Earth's gravity then drew it toward the Earth until it froze where it is today. The scale is simple arithmetic: a core of 1–2% of the lunar mass moved by a distance d moves the centre of mass by about 1–2% of d , so 2 km corresponds to d of about 100–200 km — and to more, since only the core's excess mass over the mantle it displaces counts. One fact must be faced: the Earth's gravity pulls the core and the rest of the Moon almost equally, and only the tide, which is weak, separates them. During the connection and the push of the burner the forces may have been different; that is to be computed.

The question. How much of the centre-of-mass offset, in size and in direction, is left after the crust and the topography are accounted for, and does that residual fit a core displaced toward the Earth?

What the model predicts. A residual toward the Earth, matching a core displaced by the order of 100–200 km or more. A residual of zero, or one pointing away from the Earth, leaves no room for a displaced core.

Data. LOLA topography (the centre of figure); GRAIL gravity and the GRAIL crustal-thickness models; the seismic core of about 330 km, about 1.4% of the mass (1–2%).

Method. The full offset vector computed from crust and topography with one density model (topic 112); the residual vector converted into the displacement of a core of the seismic size, with its excess density over the mantle; and a calculation of the forces that could hold the core off-centre — the tide, and the conditions of the connection and the burner — to see whether such a displacement could be reached and frozen in.

Where in the series. Paper 11 §A.7 (the total centre of mass includes the core), §B.7 (the crustal example with a symmetric core; the axis of the contact against the mean Earth line), Further work item 4; Paper 3 §E.5 makes the same kind of calculation for the Earth's core under the pear. The displaced lunar core is raised in the author's

118 An orphan minimum of crustal thickness

In the model the crust of the Moon is thinned in a few known ways. Broadly, it is thinnest over the contact and thickens through the belt to the far side (topic 107). Locally, it is thinned beneath the openings, where a feed dome rose under each mare: Paper 5 found a jump in thickness of 8 km or more beneath 29 of the 36 marked openings, against 4 of 169 ordinary craters. And it is thinned beneath the large basins. A local minimum of thickness that lies under none of these — an *orphan* minimum, neither under a basin nor under an opening — has no place in the model. Such a minimum would be a difficulty, and the crustal maps have not yet been scanned for one.

The question. Does the crustal-thickness map contain a local minimum that lies neither under a basin nor under an opening?

What the model predicts. No such minimum exists. Every local minimum of the crust lies under an opening or under a basin; the broad thinning of the contact region is the ordering of the exposure zones, not a local minimum. An orphan minimum would be a difficulty for the model.

Data. The four GRAIL crustal-thickness models (Wieczorek et al. 2013); the openings of Paper 5; the catalogue of lunar basins identified in GRAIL gravity (Neumann et al. 2015).

Method. An automatic search for local minima in each of the four models, with the depth and size of a minimum fixed before the scan — for example the rings and the 8-km threshold of Paper 5 §D.2 (centre to 0.3 radius against a ring of 1.3–2.0 radii); each minimum found is matched against the openings and the basins, and the unmatched ones are listed in all four models.

Where in the series. Paper 5 §D.2 (the crust beneath the openings and the control craters); Paper 11 §B.8 (the exposure zones); Paper 3 §B.7 (the uneven crust). The scan for an orphan minimum is raised in the author's working notes (16.10.2026 collection).

How to choose

The hundred and eighteen topics of this paper are not equal. Two of them are the key observations of the model; many can be done by one researcher with public data in months; others need a large simulation, a laboratory or a space mission. This part sorts them into three lists, so that a reader looking for a topic can find one that suits the time, the tools and the data available. The readiness of each topic is the one given in the table at the head of its part.

K.1 List 1 — the two key observations of the model

Two observations carry the model's main predictions. Both are partly measured; both can be completed.

The geometry of exposure (topics 107 and 108). The Moon should be ordered in three zones about one centre on its near side: the contact cap, exposed last, with the thinnest crust and the fewest craters; the belt around it; and the far part, exposed from the start. The table shows the two quantities measured so far. Read it from left to right: the colour deepens as the crust thickens or the craters increase, which is the direction the model requires.

Quantity	Cap	Belt	Far part	Status
Craters ≥ 20 km per 10^6 km ² , current geometry, maria and SPA removed in every zone	53	187	220	Ordering holds; far/belt 1.17, far/cap 4.15, belt/cap 3.55
Crust, Model 1, current geometry, maria kept (km)	26.3	30.3	36.2	Ordering holds; contrast 9.9 km
Crust, Model 1, current geometry, maria and SPA removed (km)	31.3	33.0	38.9	Ordering holds; contrast 7.5 km

The ordering, which is the prediction, holds in all four GRAIL models. The contrast on the September geometry, about 10 km (below), is a number for calibration.

T1: far minus contact (km)	Model 1	Model 2	Model 3	Model 4
Contrast, September geometry	9.65	10.0	10.3	10.6
Ordering cap < belt < far	holds	holds	holds	holds

RESULT

The ordering of the crust and of the craters about the near-side centre holds in every model and every count. The crustal contrast measures 9.65 / 10.0 / 10.3 / 10.6 km in Models 1-4. The rerun of all four models on the current geometry (topic 107) and the completion of T2 by age, T3, T4 and the gravity grids (topic 108) decide this observation.

The source of the craters (topics 49 and 109). In the model the craters were made by returning terrestrial material. Topic 49 reads the returning body in the crater interiors — melts and glasses compared with the candidate source mare; topic 109 decides by isotopes. The mass argument already stands, and is shown below: the colour deepens from what the crust holds to what bodies from outside would require.

Foreign material in the upper 5 km of the crust	Share
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Held by the crust (measured, at most)	0.9-2%
Needed if the visible craters were made by bodies from outside ($4.4-5.0 \times 10^{19}$ kg)	2-6%

RESULT

About 99% of the craters are made of returned terrestrial material, and the ruthenium measured so far is terrestrial. The isotopes of the metal in the Chang'e-6 norites and in the melts of the maria basins decide this observation (topic 109).

K.2 List 2 — topics that can be done now on public data

These topics need no new mission and no large code. The data are public — GRAIL gravity and crust, LOLA topography, LROC images, the Robbins (2019) crater catalogue, thorium and iron maps, sea-floor bathymetry and age grids, published sample analyses — and the method is a count, a profile, a fit or an inversion. Each can be the subject of a single paper. The table groups them by part.

Part	Topics
B. The body on the tip	19 The layered far-side crust; 21 KREEP as the torn edge of the sial; 23 Whole-Moon porosity by depth
D. The maria and the openings	31 The order of sealing; 32 Thorium at high resolution over the feed domes; 33 The rim ring of the volatile-rich maria; 34 Gradual exposure within one mare; 35 Vents and conduits; 36 The titanium part of Study 13; 37 The collar of the open far maria; 38 The pits and caves of the Moon as vapour voids; 39 The crust jump by the age of the basin; 40 The diameter of an opening by the duration of its feeding; 41 The rim of a mare as a layered record; 42 Blunt or sharp crests on the side of the plain; 43 Gravity traces of the craters that vanished into the maria

Part	Topics
E. The craters and their source	51 The longitude record; 53 The Earth as the last scatterer; 54 Material after release poorer in iron; 55 Iron of the high and low floors; 56 Crater-count ages against direct ages; 57 The rays of young craters: material within the surface
F. The poles	58 The young craters of the poles; 61 The spacing of the polar craters; 62 The marks of the shell; 64 The shallower polar craters; 65 The alignment of elongated craters; 66 The polar yardstick; 67 Crater ellipticity, and poles against the limb belt
G. South Pole–Aitken	72 Shallow craters and the minimum of depth; 73 The null test for Serenitatis; 75 The late spray of small fragments; 76 Two crater populations; 77 A direct porosity inversion; 78 The missing crust of SPA
H. The stripes and the Pacific	80–88 Stripes Studies 1–9
I. Mars and other bodies	99 Pits and grooves on Phobos; 100 The depth of the hollows; 102 The four calderas and the mass deficit beneath Pavonis
J. Requirements and key tests	107 T1 rerun on the current geometry; 108 The belt statistics completed; 115 North-south asymmetry with SPA removed; 118 An orphan minimum of crustal thickness

Topics 107 and 108 are in this list and in List 1: the most important work of the paper is also among the most accessible.

K.3 List 3 — topics that need a large simulation, a mission or samples

The remaining topics need more than public data and a short analysis. Some need new physics worked out in a model or a large simulation (orange); some need a laboratory, a returned sample or a mission (blue). The table separates the two kinds. In the orange rows the inputs are fixed by the series, so a modelling group can start at once; in the blue rows the predictions are written now, so the measurement, when it comes, is a test and not a fit.

Part	Topics
New modelling or a large simulation	
A. The Earth before and during the pear	1 Thermal expansion of the hot parent; 2 The stratified Maclaurin problem; 3 Core formation and the Hf–W history; 5 The energy of the lift; 6 The pressure test with the pear’s mass; 7 The construction rate; 8 The pear’s equilibrium figure (R9); 9 The northward lean of the pear; 10 The Earth’s core during the pear; 11 The classical fission route, recomputed
B. The body on the tip	12 A three-dimensional simulation of the connected body; 13 A stiff shell over a mobile base; 14 From $a/c \approx 1.20$ to round; 15 The drift of the release latitude; 17 The trapped pressure at detachment; 18 Survival inside the fluid Roche limit; 20 The near-side crust over the contact
C. The orbit	24 The coupled thermal–orbital integration; 25 The dissipation history of the Earth; 26 The onset of recession; 27 The magma–ocean switch; 28 The fossil figure; 29 The ancient latitude reconstructed

Part	Topics
D. The maria and the openings	30 The engine of the openings
E. The craters and their source	44 The exit velocity; 45 Passage through the steam atmosphere; 46 Shock in a hot, layered target; 48 The crater size distribution, propagated; 50 Captured ejecta after release; 52 The trailing-side excess
F. The poles	59 The figure with strength; 60 The tide on a body held by its base
G. South Pole-Aitken	68 A physical model of the heat axis; 69 A redox budget for the reduced mantle; 70 The dynamic tests recomputed; 74 A large early mare in SPA, later buried
H. The stripes and the Pacific	90 An independent reconstruction of the Pacific lithosphere
I. Mars and other bodies	91 The young Mars and its spin; 92 The gas push; 93 The soft plug; 94 Drag in the conduit; 95 The ring; 96 The climb of Deimos; 97 The race of Phobos; 105 The other bodies; 106 The poles and the spin
J. Requirements and key tests	110 A multi-system isotope balance (R1); 111 The metal budget (R2, R13); 112 The joint crust-centre-of-mass solution (R3, R7); 114 Volatiles the feed needs (R6); 117 The core offset as the residual of the centre-of-mass offset
A mission, samples or new laboratory data	
A. The Earth before and during the pear	4 The equation of state of the deep melt at 50–150 GPa
B. The body on the tip	16 Stefan adhesion and the failure of the contact; 22 High-pressure phases in contact-zone samples
E. The craters and their source	47 The trend in a series of events; 49 Seeing the returning body, not the ground
F. The poles	63 The innermost caps
G. South Pole-Aitken	71 The volatile and redox gradient across the basin; 79 Vapour that evaporated metals in SPA, and where it went
H. The stripes and the Pacific	89 The Pacific province as the returned pear (plume isotopes)
I. Mars and other bodies	98 The samples of MMX; 101 The centre of mass of Phobos; 103 The Martian dust; 104 One conduit on the equator (R18)
J. Requirements and key tests	109 The isotopic decision (R14); 113 Two crusts, two ages (R5); 116 The composition of the lunar core

Of the large simulations, topic 12 (the connected body in three dimensions) and topic 24 (the coupled thermal-orbital integration) carry the most: the first follows the body from construction to release, the second carries it from release to today's orbit. Of the missions, MMX decides four topics at once (97, 98, 100 and, through the age of Deimos, 104).

Future work outside this paper

Two subjects are named in the series as future work and are not numbered here. The first is the system of axes of the Earth and the Moon from release to today: four planes — the Earth's equator, the Moon's orbit, the Moon's equator and the ecliptic — moving in two kinds of motion at different rates, with an unknown memory held by a frozen bulge. Its first step is the obliquity channel: the tilt of 3.8° given to the Earth's spin

at release, and whether the coupling of Sun, Earth and Moon grew it or damped it on the way to today's 23.44°; a change of the Earth's axis after separation may also make South Pole–Aitken appear out of line with the burner. The second is the magnetism of the Moon: the source of its ancient field, and its pattern over South Pole–Aitken — erased at the centre, strong on the trailing side, with the swirls of Ingenii — read in the series as a record of heat and of iron from the Earth. It includes the test of the depth and direction of the magnetisation, which should be strongest at the margins of the heated core and sourced at depth.

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- LROC: Lunar Reconnaissance Orbiter Camera (WAC and NAC), NASA Planetary Data System.
- MMX: Martian Moons eXploration, Japan Aerospace Exploration Agency (JAXA).

Use of AI tools: The author used AI assistants (Claude, Anthropic; ChatGPT, OpenAI; Google's AI search assistant) to write and run the computation scripts, to analyse the catalogues and maps, to prepare figures and tables, to discuss the scenarios, and for language editing and translation. The model and its conclusions are the author's. The author checked the content and takes full responsibility for it.