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Sublimation driven convection in Sputnik Planitia on Pluto

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Sputnik Planitia is a nitrogen ice filled basin on Pluto¹. Its polygonal surface patterns² have been previously explained as a result of solid state convection with either an imposed heat flow³ or a temperature difference within the 10 km thick ice layer⁴. Neither explanation is satisfactory, because they do not exhibit surface topography with the observed pattern: flat polygons delimited by narrow troughs⁵. Internal heating produces the observed patterns⁶, but the heating source in such a setup remains enigmatic. Here we report the results of modeling the effects of sublimation at the surface. We find that sublimation driven convection readily produces the observed polygonal structures if we assume a smaller heat flux ($\sim 0.3 \text{ mW m}^{-2}$) at the base of the ice layer than the commonly accepted value of $2 - 3 \text{ mW m}^{-2}$ [ref 7]. Sustaining this regime with the latter value is also possible, but would require a stronger viscosity contrast (~ 3000) than the nominal value (~ 100) considered in this study.

Ice sublimation is a common geomorphic process at the surface of solid planets⁸: for instance, sublimation of carbonic ice draws a variety of spectacular depressions on the Martian south polar cap. On Earth, penitentes observed in high altitude deserts are attributed to snow sublimation.^{9,10} In the outer solar system, some of Pluto's terrains rank among the most emblematic landforms created by sublimation. In summer 2015, the flyby by the New Horizons spacecraft revealed that Tombaugh Regio, sitting slightly North of Pluto's equator, is the richest province in this regard¹¹. Owing to the specific nature of Pluto's tenuous atmosphere, N_2 , its most abundant constituent, is considered to be the key ingredient. 1000-km wide Sputnik Planitia (SP, the western part of Tombaugh Regio) is shown by climatic models^{12,13} to provide the dominant source of nitrogen ice involved in climate cycles. Ice cycles are driven by intense condensation and sublimation on annual to astronomical timescales. Typical daily sublimation rates could reach values of $4.2 \times 10^{-7} \text{ kg m}^{-2} \text{ s}^{-1}$ in the north of SP. Even in regions where sublimation may be less predominant such as the central-south bright cellular plains², pronounced

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pits attest that net sublimation occurs at the surface in spite of the possible deposition of fresh N_2 ice responsible for the high albedo. Their distribution enables the estimation of surface flow and age of the individual cells¹⁴ Furthermore, we propose that sublimation constitutes the so-far enigmatic engine that powers convection in SP.

In many common-life situations, cooling can be induced by evaporation of water in a dry environment. For example, this is the way perspiration is used by the human body to regulate its temperature in hot weather. Physically, latent heat is required for evaporation and this leads to cooling of the skin. Similarly, the sublimation of ice leads to cooling of its surface. Sublimation happening at the surface of SP on Pluto¹¹ provides a source of negative buoyancy that can drive thermal convection if it overcomes viscous resistance and proceeds faster than thermal diffusion, i.e. if the associated Rayleigh number is higher than the critical value of order 10^3 .

Thermal convection in a water pool driven by evaporation at the surface¹⁵ provides a common-life guide to the theory exposed here for Pluto. The solid-vapour phase equilibrium at the horizontal surface implies the application of Stefan's condition:

$$-k \frac{\partial T}{\partial z} + h(T_\infty - T^+) = LI_s(T^+), \quad (1)$$

with k the thermal conductivity of ice, T the temperature in the ice, taking the laterally-variable value T^+ at the surface, T_∞ the temperature of the bulk of the atmosphere, h an exchange coefficient characterising the balance between insolation and radiation of the surface (methods), L the latent heat of sublimation and $I_s(T^+)$ the mass rate of sublimation at the relevant temperature. Starting with an ice layer at uniform temperature T_∞ , sublimation can only proceed by decreasing T^+ , so that both terms on left-hand-side are positive. The maximal temperature difference $(T_\infty - T^+)$ that can be produced by this process is for a uniform temperature in the solid denoted T_s . This provides the temperature scale for our physical problem: $\Delta T_m = T_\infty - T_s$. Using $\theta = (T - T_s)/\Delta T_m$ as dimensionless temperature and the thickness d of the layer as length scale, the dimensionless boundary condition at the surface of the ice layer is

$$\frac{\partial \theta}{\partial z} + Bi\theta = 0, \quad (2)$$

$Bi = Hd/k$ being the Biot number, with H the effective exchange coefficient (methods). The temperature scale ΔT_m can also be used to construct the nominal Rayleigh number,

$$Ra_\infty = \frac{\alpha \Delta T_m \rho g d^3}{\kappa \eta_\infty}, \quad (3)$$

with α the coefficient of thermal expansion, ρ the density, g the acceleration of gravity, κ the thermal diffusivity and η_∞ the viscosity at T_∞ (methods).

Many parameters entering the definition of the two dimensionless numbers defined above are quite uncertain. Typical values are given in table 1 (methods). With these figures, we estimate typical values of the Rayleigh number, $Ra \sim 5.5 \times 10^4$, and Biot number, $Bi \sim 100$, that clearly allow for convection to develop in Sputnik Planitia. The large value of the Biot number implies that the energy driving sublimation is primarily derived from insolation. However, this makes the surface temperature decrease which drives convection in the solid.

We used the solid-state convection code StagYY¹⁶ and ran calculations for various values of the Rayleigh number and viscosity contrast, $R_\eta^\infty = \eta(T_s)/\eta_\infty$, assuming a Newtonian rheology for simplicity (methods). Calculations are started with a uniform temperature T_∞ and the domain cools down due to the boundary condition at the surface (2). After a transient, whose

duration depends on the input parameters but is typically less than a few 100 kyr for vigorously convecting cases, convection is established. We consider the pattern obtained after the transient period and fig. 1(a) shows a map of the obtained surface topography. As a comparison, fig. 1(b) shows an equivalent map obtained for convection driven by an imposed temperature difference, which produces a polygonal pattern with topographic highs as sides to the polygons, at odds with the observations⁶. Convection driven by sublimation (fig. 1a), on the other hand, produces polygons whose sides are the topographic lows caused by downwelling currents, hence the converging regions, as is the case for SP¹⁴.

We explored systematically the parameter space in the range $10^4 \leq Ra_\infty \leq 10^7$ and $10 \leq R_\eta^\infty \leq 10^5$ and obtained 4 different regimes of convection, three of which displayed on fig. 2. For low viscosity contrasts (fig. 2(a)), the convective pattern is similar to iso-viscous cases with cold down-welling plumes, separated by a distance of the same order as the thickness of the layer. The horizontal velocity reaches its maximum at the upper surface (methods) and the surface topography is too low in amplitude to show up in figure 2. For large viscosity contrasts (fig. 2(c)), the cold upper boundary layer is difficult to deform, leading to the sluggish or stagnant lid regimes^{17,18}, for which the horizontal velocity is smaller at the upper surface than in the bulk of the layer, or even null in the latter case. For intermediate values of the viscosity contrast (fig. 2(b, d)), the convective regime assumes a polygonal planform which best explains observations of SP. Using the vertical profiles of the horizontal velocity and the number of cold plumes detected at mid-depth (methods) allowed us to produce a regime diagram (fig. 2(e)). Since the effective range of temperature encountered in the calculation depends on time, the viscosity contrast and the Rayleigh number actually realised are time-dependent and result from the calculation. The domain of polygonal solutions expands upon increasing Ra_{eff} and R_η and the estimated values for Sputnik Planitia place it in that regime.

The least well constrained parameters entering the Rayleigh number are the layer thickness, in the 1 km to 10 km range^{3,4,19,20}, and the viscosity in the bulk of the N₂ ice layer, in the 10^{10} Pa s to 10^{19} Pa s range^{21,22}. Having identified five cases in the polygonal regime, the value of their Rayleigh number can be used to assess the trade-off between these two parameters, assuming all other parameters take their nominal value in table 1. This is done in figure 3a where the surface viscosity value is indicated. The latter is considered to exceed 10^{16} Pa s to 10^{17} Pa s from the observation of unrelaxed sublimation pits in SP's cellular plains¹⁴. All five cases involve acceptable viscosities, albeit only for the largest values of the layer depth and only marginally for cases 13 and 6 (blue and green in figure 3a).

The dimensional surface velocity v_t and the average size of polygons L_p (methods) are linked to their dimensionless counterpart, denoted by primes, by $v_t = v'_t \kappa / d$ and $L_p = L'_p d$, which can be used to get $v_t = v'_t L'_p \kappa / L_p$. Direct observation of Sputnik Planitia² shows that the size of polygons ranges from 7.7 km to 102.8 km with a median value of 26.6 km. All five cases in the polygonal regime provide a median value of L_p that enters this range except for the smallest values used for the layer depth d (Fig. 3b). The surface horizontal velocity has also been estimated from a model of sublimation pits formation for seven polygonal cells with dimensions close to the median size¹⁴. Values range between 4.8 cm yr^{-1} and 31.6 cm yr^{-1} and are displayed with uncertainties in figure 3b. Again, the five simulations involve values for the RMS of v'_t that are well in line with the ones estimated for these seven polygons.

The numerical results can also be used to predict other potentially observable characteristics of SP, such as the amplitude of the dynamic topography. Figure 3(c) shows the values obtained for all five polygonal cases, in the range of ice thickness for which figure 3(b) falls in the L_p range. The amplitude of dynamic topography ranges from 50 m to 3 km. We note here that dynamic topographies are not directly observed at the surface of SP. For instance, non-ice materials such

as tholins are expected to accumulate in the troughs constituting the cells' edges^{2,23,24}. As a result, the 200 m topography estimated by Schenk *et al.*⁵ from stereo data acquired by New Horizons for a 30 km-wide cell shall be considered as a minimal value.

The simulations presented above assume that sublimation is occurring uniformly over SP at a constant rate throughout the evolution. Long term insolation²⁵ and volatile transport¹³ models predict however spatial as well as temporal fluctuations. While sublimation is attested immediately at the surface of SP (atmospheric temperature profiles²⁶, imaged pits), the effect of condensation is less obvious. Overall, the condensation budget is not sufficient to inhibit the growth of pits over timescales of 10^5 yr.¹⁴ This is consistent with our analysis of the current planform (with troughs at polygons' boundaries) as evidence that surface cooling is predominant over basal heating (methods). Diurnal (6.4 Earth days) and even seasonal (250 Earth years, methods) variations are too short to significantly affect the results presented above. On the long astronomical timescale however, the dynamics of Pluto's major N₂ ice glacier is necessarily transient. While the formation and age of SP are unconstrained and impossible to evaluate on the sole basis of our calculations, the cumulated duration of the initial transient stage as well as a prior convective evolution before the occurrence of the polygonal regime in SP could amount to a significant time lapse. In our simulations, as it emerges from the reorganization of primary convective instabilities such as shorter-scale plumes and sheet-like downwellings, the long-wavelength polygonal pattern involves a maturation stage whose duration could typically last several tens to several hundreds kyr (extended data table 1). Adding the apparent age of the edges of polygons (a few hundreds of kyr)¹⁴, the convective process in SP could be at least as old as 1 Myr, in line with the occurrence of an increase of surface temperature in the high albedo, low-latitude SP predicted by insolation models²⁵, still observed at present. Repeated episodes of net sublimation associated to higher obliquity with a period of ~ 3 Myr can be envisioned in the past (e.g. between 3 and 4.5 Myr ago)¹³ where the present convective pattern could have occurred.

Our results demonstrate that, besides small-scale morphogenesis⁸, ice sublimation can also generate planetary-scale patterns as a buoyancy sink driving solid-state convection. Convective dynamics in SP are actively intertwined with Pluto's climate. In that sense, this multi-kilometer-thick regional N₂ layer on Pluto relates more to Earth's oceans than to other convecting ice layers on some of Jupiter's or Saturn's moons, mostly forced by heat extraction from the interior. While uniquely identified so far in the specific case of Pluto, other planetary bodies might host similar phenomena. For this process to happen, a low-viscosity volatile ice (N₂, CO, CO₂ or possibly CH₄) must be abundant at the surface and the object massive enough to retain the associated volatile. Among icy moons closer to the sun, Triton²⁷ or Umbriel²⁸ are thus certainly plausible candidates. Among the largest TNOs, natural candidates are Eris²⁹ and Makemake³⁰.

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Author Contributions All authors developed the theory and designed the study together. AM modified the StagYY code, AM and SL ran the calculations and developed the analysis python scripts. All authors contributed to the paper.

Table 1: Parameter values. Values come from the cited references. Estimates for d , η_∞ and I_s are discussed in methods.

Parameter	Nominal value
Layer thickness, d	5 km
Surface temperature ²⁶ , T_s	37 K
Thermal conductivity ³¹ , k	0.26 Wm ⁻¹ K ⁻¹
Thermal diffusivity ³¹ , κ	1.44 × 10 ⁻⁷ m ² s ⁻¹
Density ³¹ , ρ	990 kg m ⁻³
Thermal expansion ³¹ , α	2 × 10 ⁻³ K ⁻¹
Acceleration of gravity ³² , g	0.642 m s ⁻²
Effective viscosity at $\sigma_{II} = 0.1$ MPa, η_∞	10 ¹⁴ Pas
Latent heat ³² , L	2.25 × 10 ⁵ J kg ⁻¹
Maximum temperature difference ^{13,26} , ΔT_m	5 K
Sublimation rate, I_s	10 ⁻⁷ kg s ⁻¹ m ⁻²
Effective exchange coefficient, H	4 × 10 ⁻³ W m ⁻² K ⁻¹
Rayleigh number, Ra	5.5 × 10 ⁴
Biot number, Bi	100

Competing interests The authors declare no competing interests.

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Figure 1: Dynamic topography at the surface of a convecting ice layer driven by sublimation (a, case #6) or an applied temperature difference (b) for $Ra_\infty = 10^6$ and a nominal viscosity contrast $R_\eta^\infty = 100$. See methods for the computation of topography.

Figure 2: Pattern of convection obtained as function of viscosity contrast and Rayleigh number. Snapshot of mid-depth temperature anomaly (a, b, c) and of surface topography and horizontal velocity (d) are shown for cases # 10 (a), 14 (b, d) and 16 (c) (see extended data table 1 for parameters) in the weak-viscosity contrast, polygonal, and stagnant lid regimes, respectively. All lengths have been scaled using 5 km as thickness for the ice layer. The same color scale is used for temperature (a, b, c). (e) Regime diagram as function of effective Rayleigh number and viscosity contrast (eq. 12). Shapes and colors of symbols give the regime. Numbers surrounding squares and hexagons are the number of cold plumes at mid-depth (left) and of connected high-topography regions at the surface (right).

Figure 3: Application of cases in the polygonal regime (solid coloured lines) to Sputnik Planitia. (a) Viscosity of the N_2 ice at the surface as function of the layer thickness for the polygonal cases identified in fig. 2. The minimal value (horizontal dashed line and vertical arrow) is estimated by Buhler & Ingersoll¹⁴ from a growth model for sublimation pits. (b) Root-mean-square horizontal velocity at the surface as a function of the polygon size for the runs in the polygonal regime. The ends of each line correspond to the bounds on the layer thickness, 1 km to 10 km. The error bar points have been derived for 7 cells from the model of sublimation pits¹⁴. The blue region gives the range of polygon sizes observed on SP, the dashed line being the median². (c) Amplitude of topography predicted from the cases in the polygonal regime as function of the ice thickness. As in (c), the blue region denotes the range of polygon sizes on SP. The estimated minimum obtained by Schenk *et al.*⁵ for one polygonal cell is indicated (dot and arrow). (d) Time to establish the polygonal regime as solid coloured lines and the additional 0.5 Myr minimum age of the surface¹⁴ as coloured shaded area. The range of ice thickness in (c) and (d) is limited to that satisfying the bounds on polygonal sizes from panel (b). Values of the ice thickness d and horizontal velocity v_h in the legend box are obtained for the median value of the cell sizes, as represented by the vertical dashed line in (b) and (c).

A Methods

A.1 Sublimation boundary condition

The interaction between the dynamics of the atmosphere and that of the N_2 ice layer is complex and we do not claim solving it fully. Atmospheric models, at best, generally consider the heat flow from the solid as uniform. Conversely here, we consider the atmosphere as a well mixed envelope that applies uniform boundary conditions to the ice layer. This requires the derivation of a boundary condition that is simplified compared to the full problem while keeping its salient aspects, in particular the proper balance of the different implied terms. The derivation follows the same approach as that used in many studies of convection driven by evaporation^{15,33} and includes a phenomenological exchange coefficient. The use of this coefficient is common practice

in the heat transfer literature but it is desirable to relate to a more physical description of the different processes at play, which is the object of this section.

As for any boundary at which a phase change occurs³⁴, the energy balance states that the heat flux discontinuity equals the latent heat released or consumed,

$$q^+ - q^- = -L \frac{dm}{dt}. \quad (4)$$

with q^+ and q^- the heat fluxes on the upper and lower sides of the boundary, respectively, L the (positive) latent heat of sublimation and $\frac{dm}{dt}$ the rate of sublimating mass per unit surface. Heat fluxes are counted positive upward and if $q^+ - q^- > 0$ condensation happens, i.e. $\frac{dm}{dt} < 0$. The heat flux from below is given by Fourier's law:

$$q^- = -k \left. \frac{\partial T}{\partial z} \right|_s, \quad (5)$$

z being again counted positive upward and the subscript s indicating that it applies at the surface. The heat flux on the upper side toward positive values of z ,

$$q^+ = -S_0(1 - A) + \varepsilon\sigma(T^+)^4, \quad (6)$$

contains two contributions, that from the solar insolation S_0 limited by the albedo A , counted negative since it comes from above and the radiation from the surface at laterally-variable temperature T^+ , with an emissivity ε , σ being the Stefan-Boltzmann constant. The general equation can then be written as

$$-k \left. \frac{\partial T}{\partial z} \right|_s + S_0(1 - A) - \varepsilon\sigma(T^+)^4 = L \frac{dm}{dt}. \quad (7)$$

In situation of thermal equilibrium at the boundary, that is without sublimation or condensation, the surface temperature assumes a value equal to T_∞ which is set by

$$S_0(1 - A) - \varepsilon\sigma T_\infty^4 = 0. \quad (8)$$

Assuming that the surface temperature stays not too different from T_∞ , we can linearize the radiative term in the energy balance (7) around T_∞ to give

$$-k \left. \frac{\partial T}{\partial z} \right|_s + 4\varepsilon\sigma T_\infty^3(T_\infty - T^+) = L \frac{dm}{dt}. \quad (9)$$

We recover the boundary condition written in equation (1) by setting $h = 4\varepsilon\sigma T_\infty^3$. Other contributions could be added to this term, for example the convective heat transfer in the atmosphere that should also be proportional to the temperature difference between the surface and the overlying atmosphere, to first order. This shows that the exact value of h is difficult to pin down but, fortunately, the problem can be circumvented by using the temperature profile observed by the New Horizon REX experiment, as explained in the main text.

Note that the energy balance equation (7) written here differs slightly from that used by Hansen & Paige [35] because they consider the energy budget of a thin frost between a substrate and the atmosphere while we consider here the balance at the interface between a thick layer of N₂ ice and the atmosphere.

Assuming local thermodynamical equilibrium at the ice surface, temperature and sublimation rate are linked through the phase diagram. $I_s(T^+)$ can be developed linearly around T_∞ to write equation (1) as

$$-k \frac{\partial T}{\partial z} + H(T_\infty - T^+) = LI_s(T_\infty), \text{ with } H = h + L \frac{\partial I_s}{\partial T}(T_\infty). \quad (10)$$

The maximum value of $(T_\infty - T^+)$ is obtained for a uniform temperature in the ice (T_s) i.e. by setting $\frac{\partial T}{\partial z} = 0$. This provides a temperature scale $\Delta T_m = T_\infty - T_s = LI_s(T_\infty)/H$. Rendering this equation dimensionless leads to equation (2).

A.2 Convection models

The mantle convection code StagYY¹⁶ solves the momentum and energy balance equations using finite volumes for an infinite-Prandtl-number fluid with temperature-dependent viscosity subjected to gravity action. Equations are made dimensionless with the thickness of the domain d , the thermal diffusion timescale d^2/κ , the temperature scale ΔT_m (see text) and the reference dynamic viscosity $\eta_\infty = \eta(T_\infty)$. The numerical domain is a $16 \times 16 \times 1$ box, using $1024 \times 1024 \times 64$ grid points with a factor 5 grid refinement in the top boundary layer. This aspect ratio is large enough to allow the large patterns observed in the polygonal regime to develop. Boundary conditions are periodic on vertical sides of the box. The bottom boundary is rigid ($\mathbf{v} = 0$) and thermally insulating ($\partial\theta/\partial z = 0$). The top boundary is free-slip, and as discussed in the main text, the top boundary condition on temperature relates the heat flux to the surface temperature through the Biot number (see eq. 2). The Biot number being large (~ 100 , see Table 1), this boundary condition is close to that of a fixed temperature, $\theta = 0$ (i.e. $T = T_s$ in dimensional form), which we considered in our calculations. As a sanity check, we performed a run at $Bi = 100$ which yielded nearly the same results as the fixed-temperature boundary condition.

The initial condition is $\theta = 1$ (i.e. $T = T_\infty$) in the solid domain. The $\theta = 0$ boundary condition at the top as well as the nul heat flux at the bottom of the domain lead to its cooling. The convective patterns shown in this paper are therefore transient as the only possible steady state is a uniform $\theta = 0$ temperature in the solid. Temporal alternance between sublimation and solidification is required to sustain this mode of convection over abitrarily large periods of time.

We consider a Newtonian rheology since the stress-strain rate exponent, $n = 2.1$ [ref 22] is small. The dynamic viscosity in the domain depends only on temperature T and is assumed to follow an Arrhenius law, which in dimensionless form reads:

$$\eta = \exp\left(\frac{E_\eta}{\theta + 1} - \frac{E_\eta}{2}\right). \quad (11)$$

E_η controls the initial viscosity contrast $R_\eta^\infty = \eta_\infty/\eta(T_s)$. Note that since the temperature in the domain decreases with time, the effective viscosity contrast $R_\eta = \eta_{\max}/\eta_{\min}$ decreases with time. In this study, initial viscosity contrasts span from 10 to 10^5 , imposed via the input parameter $E_\eta = 2 \ln R_\eta^\infty$.

A.3 Parameter values

Input and output parameters in the convection code are dimensionless and extended data table 1 provides a list of all cases ran for this study. Several parameters deserve a specific discussion in the following subsections.

A.3.1 N₂ layer thickness

Owing to the quasi-circular rim of mountains surrounding it, the SP basin is considered to result from an impact¹. Its depth is however a matter of debate: an initial value of ~ 7 km is proposed on the basis of a comparison with the shape of unrelaxed craters observed on Iapetus and the Moon¹⁹. Models of convection in SP generally propose values of a few kilometres⁴ for the thickness d of the nitrogen glacier, possibly up to $d \sim 10$ km [ref 3]. An independent constraint based on a possible reorientation of Pluto provides similar estimates²⁰. We consider a reference value of $d = 5$ km.

The floor of the N₂ ice layer is not expected to be flat: the bedrock beneath the surface of SP is probably located deeper at its center, as envisaged by Bertrand et al.¹³. While such thickness variations are not accounted for in our models, these are expected to lead to lateral variations in the effective Rayleigh number as well as the characteristic length scale. While the latter would practically induce a larger width of convection polygons at the center of SP relative to its periphery, the effect of a varying Rayleigh number is more complex to predict on the basis of our simulations.

A.3.2 Viscosity

The rheological properties of N₂ are still largely uncertain at the conditions appropriate for the SP convecting glacier. Two studies provide divergent values for viscosity. Eluszkiewicz and Stevenson²¹ summarized data on CH₄ and N₂ ice grains, mostly in the framework of diffusion (Newtonian) creep. Yamashita et al.²² conducted laboratory experiments for non-Newtonian creep of annealed solid N₂. Reviews^{14,32} have already reported that values inferred from the two above models could differ by 6 to 9 orders of magnitude for parameters relevant for the surface of SP: the non-Newtonian creep model implies extremely low values ($\eta \sim 10^{10}$ Pa.s) while the diffusional creep data favors much larger values ($\eta \sim 10^{16} - 10^{19}$ Pa.s). For our models, we note that possible observational constraints for the SP ice viscosity could be derived from the strength required for the ice crust to oppose the erasure of sublimation pits by viscous relaxation^{11,14}: reasonable values lie in the range ($\eta \sim 10^{16} - 10^{17}$ Pa.s). Given the viscosity contrast between the cold viscous surface and the interior in our successful models (typically a few tens to a few hundreds), we opt for a value of ($\eta \sim 10^{14}$ Pa.s) to characterize the viscosity of the bulk convecting interior of the glacier.

We further note that the values for the effective activation energy associated to the two rheological models strongly differ³²: for the non-Newtonian creep, 3.5 kJ mol^{-1} , for the Newtonian creep, 8.6 kJ mol^{-1} . Our models help illuminate the thermal and mechanical contributions to the viscosity variation. In case #14 shown in Fig. 2 of the main text, for instance, the global contrast $\eta_{max}/\eta_{min} = 98.5$ (see extended data table 1). Assuming a surface temperature of 37 K, a purely thermal explanation of this viscosity contrast would involve a temperature difference of 7 K or 25 K for an activation energy equal to 8.6 kJ mol^{-1} or 3.5 kJ mol^{-1} , respectively. The same viscosity ratio could be obtained using a stress-dependent rheology. This would require a contrast of strain rate of about 6×10^3 across the convecting layer for a stress exponent ~ 2.1 . Complete self-consistent models with this rheology are still needed to test whether the polygonal regime can be obtained and in what parameter range. Other effects, such as the presence of impurities resulting in an increase of viscosity, can certainly be envisaged although the vertical enrichment in such impurities towards the surface of SP remains to be explained and quantified. Overall such non-thermal explanations are less appealing as they would correspond to major departures from the sublimation-driven convection model presented here. The Newtonian model explored here is reasonable as a temperature difference of a few

kelvins is sufficient to induce the required viscosity contrast corresponding to all cases presented for the polygonal regime (Fig. 2). If, however, larger viscosity contrasts are considered (e.g. high-Rayleigh number cases displayed in extended data figure 11 and 12), a larger activation energy or other contributions to the viscosity contrast must be envisaged. For instance, variations in grain size across the layer thickness (not taken into account in our models) would also contribute to viscosity variations.

A.3.3 Sublimation rates at the surface of Sputnik Planitia and its spatial variations

The sublimation process at the surface of SP has been modeled in a global circulation model¹². Sublimation rates obtained in this model strongly vary with latitude: on a daily basis, rates as high as $4.2 \times 10^{-7} \text{ kg m}^{-2} \text{ s}^{-1}$ are modeled in the north of SP where insolation is higher, while $-1.6 \times 10^{-7} \text{ kg m}^{-2} \text{ s}^{-1}$ (i.e. condensation) is obtained closer to the equator. Similar figures are obtained for daily rates in a study also considering seasonal and astronomical timescales¹³: when averaged over one Pluto year (248 Earth yr), sublimation rates are significantly smaller (by 2 orders of magnitude). Selecting the effective (uniform) sublimation rate is uncertain as the precise effect of condensation immediately at the surface of SP or in the overlying atmosphere is unclear. Furthermore, locally, transport of cold N_2 gas produced at larger latitudes is found to be spread throughout the basin by Global Climate Models¹². GCMs with an improved resolution²³ further demonstrate the role of topographic effects and transport of dark materials that likely induce longitudinal variations.

A conservative lower limit on the actual average sublimation rate might be brought by the radial growth rate of sublimation pits ($2 \times 10^{-8} \text{ kg m}^{-2} \text{ s}^{-1}$) over hundreds of thousand years at the surface of SP¹⁴. Note that this value is obtained for sublimation pits observed in the south of SP, where the climatic model of Bertrand *et al.* [13] predicts net condensation in the current season. Of interest is the increased power received by pits relative to a flat surface, owing to scattering of sunlight for their specific geometry. This results in an enhanced sublimation rate^{10,14}.

We choose an intermediate rate of $10^{-7} \text{ kg m}^{-2} \text{ s}^{-1}$ to evaluate the reference Rayleigh and Biot numbers. We emphasize that the temperature scale used to compute the Rayleigh number values associated to our simulations is independent of these uncertain estimates: it relies on the atmospheric temperature profile measured by the REX experiment (§ A.3.4). Similarly to a radial decrease in the N_2 layer thickness, spatial variations of the sublimation rate over specific regions of SP will induce lateral (possibly mostly latitudinal) variations in the Rayleigh number.

Finally, we investigate in a few dedicated simulations the effect of intermittent sublimation over seasonal timescales (see A.7 below).

A.3.4 Temperature scale

In the atmospheric temperature profile retrieved by the New Horizons REX experiment above the surface of SP²⁶ a local temperature minimum is observed, interpreted in the climate model of Forget *et al.*¹² as a result of the release of cold sublimated N_2 gaz. This minimum is at about 35 K, yielding a temperature jump of a few K as the surface temperature is in the range 40–43 K¹³. We use $\Delta T_m = 5 \text{ K}$ in the estimate of the Rayleigh number.

A.4 Analysis of results

Since the overall domain cools down, its average temperature $\bar{\theta}$ decreases while its log-average viscosity $\bar{\eta}$ increases. To integrate this effect in the comparisons of the runs, we use the effective Rayleigh number Ra_{eff} instead of the nominal value Ra_{∞} :

$$Ra_{\text{eff}} = Ra_{\infty} \frac{\bar{\theta}}{\bar{\eta}}. \quad (12)$$

The dynamic topography Δh at the surface of the model is computed as that needed to balance the viscous stress on an undeformed boundary, as

$$\Delta h = \frac{\alpha \Delta T_m \bar{\theta}}{Ra_{\text{eff}}} \left(p - 2\eta \frac{\partial v_z}{\partial z} \right) \quad (13)$$

where p is the dynamic pressure, $\bar{\theta}$ is the dimensionless temperature of the ice layer and Ra_{eff} is the effective Rayleigh number for the analysed snapshot. The term in parentheses is the stress applied by the convective matter at the surface of the domain. The dimensional topography is recovered by multiplying Δh with the depth of the domain d . This approach is valid under the assumptions of a small topography, $\Delta h \ll 1$, and small topography slope $\|\nabla_h \Delta h\| \ll 1$. These conditions are verified except for very restricted areas in two cases. Looking at extended data table 1, one can check that the peak-to-peak topography is lower than 10% except for two cases (# 14 and 15) where the RMS topography is nevertheless lower than 10%. Inspection of the topography figures for these cases (Supplementary information) shows that a very small area concentrates the most negative values. The mean slope of the topography can be computed as $\sqrt{(\partial_x h)^2 + (\partial_y h)^2}$ and is shown on extended data figure 1 for the same cases. The slope is very small except in very limited areas that mark the sides of polygons. These small areas are regions where the approximation leading to the calculation of topography may break down. We expect that viscous deformation in these high topography slope regions leads to limiting the topography amplitude in a diffusion-like process³⁶ but the details of that depend strongly on the actual rheology. In particular, a topography on such a small area could be sustained elastically for long time periods.

Polygons are counted as connected components to build the regime diagram on Fig. 2(e). The number of polygons is the number of connected components of positive topography, as calculated with eq. (13). This strategy leads sometimes to the detection of small transient topographic highs in globally downwelling areas where limits of various polygons meet and merge together. These spurious detections are difficult to avoid; using an arbitrary threshold (instead of 0) to define topographic highs can indeed eliminate well-formed polygons. Since the number of spurious detections is low compared to that of well-formed polygons, we therefore choose here for simplicity to count any positive topography as being part of polygons. Furthermore, polygons with a typical size $L_p < 1$, i.e. smaller than the layer thickness, are removed from the count. L_p is computed as the square root of the surface of the polygons.

Similarly, cold plumes are counted as connected components of “low” temperature on an horizontal plane at mid-depth³⁷. The threshold temperature we use to count cold plumes is $(\theta_{\min}(z) + \theta_{\text{mean}}(z))/2$. This arbitrary threshold is found to yield a meaningful number of cold plumes (without losing too many cold structures nor artificially grouping separated downwelling). Moving slightly this threshold around the chosen value would change the number of cold plumes but the general trend observed on Fig. 2(e) is robust against such changes.

Finally, we identified 4 different regimes of convection in our simulations. The criteria we used for this classification are based on the number of cold downwellings at mid-depth N_c , and

on the ratio R_v between the root-mean-square horizontal velocity at the surface of the domain and the maximum rms horizontal velocity in the domain. Note that although these criteria are somewhat arbitrary, they successfully group together simulations exhibiting similar convective patterns (see table of all cases in supplementary information).

Stagnant lid defined as $R_v < 0.1$. This regime is characterized by almost no movement at the surface, the lid being too rigid to be involved in convective motions.

Sluggish lid defined as $0.1 \leq R_v < 0.9$. This regime exhibits a very small topography at the surface, with limited motion of matter at the surface.

Low viscosity contrast defined as $R_v \geq 0.9$ and $N_c > 90$. This regime exhibits a small topography at the surface, with a large number of up- and down-wellings.

Polygonal defined as $R_v \geq 0.9$ and $N_c \leq 90$. This regime exhibits a large topography and a long-wavelength organisation of the flow at the surface.

A.5 Transient nature of the evolution of SP

All calculations are started from a uniform temperature (dimensionless value 1) and submitted at $t = 0$ to a zero (dimensionless) temperature at the top. The cooling of the interface leads to the development of a cold boundary layer that eventually forms instabilities, which marks the onset of convection. The pattern of convection then evolves with time and we show in the supplementary video the development of convection from the start in the case shown on figure 2(b,e) of the main text. In addition, extended data figure 2 shows the evolution with time of several key diagnostics, the surface heat flux q_{surf} , the mean temperature $\langle T \rangle$, the RMS velocity v_{rms} , the effective Rayleigh number Ra_{eff} and the viscosity contrast $\eta_{\text{max}}/\eta_{\text{min}}$. The initial diffusive stage, the onset of convection and the establishment of a slowly evolving regime can be easily identified.

By design, our models are transient. As shown in extended data figure 2, continuous cooling of the surface induces a decrease of the driving temperature gradient and consequently an increase of the interior viscosity. As a result, the Rayleigh number decreases throughout a given calculation. Introducing the equivalent volumetric heating rate associated to the mean cooling of the layer, $H = -\rho C_p (\partial \langle T \rangle / \partial t)$ (with $\langle T \rangle$ the average temperature), a characteristic temperature scale is $\Delta T_H = Hd^2/k$. The typical evolution is then conveniently displayed in a diagram relating the average dimensionless temperature $\theta_H = (\langle T \rangle - T_s) / \Delta T_H$ to the Rayleigh number defined as $Ra_H = (\alpha \rho g \Delta T_H d^3) / (\kappa \eta)$ [ref 38]. This is displayed in extended data figure 3 for case # 14, whose last snapshot is presented on fig. 2. A typical evolution involves first a conductive transient followed by the onset of convection which makes θ_H drop. Convection first takes the form of boundary layer instabilities which sets their short wavelength (extended data figure 4, $t = 17.7$ kyr, snapshot 2 on extended data figure 3) followed by a maturation phase that sees a larger wavelength develop (extended data figure 4, $t = 88.6$ kyr, snapshot 10 on extended data figure 3). The polygonal regime is finally established (extended data figure 4, $t = 1.6 \times 10^2$ kyr, snapshot 18 on extended data figure 3) and, in this regime, $\theta_H \propto Ra_H^{-1/4}$ as for classical volumetrically heated convection³⁸. The duration of the maturation period needed to establish the polygonal regime has been computed for the 5 relevant cases using the same criteria as presented in the methods section and the dimensionless values are given in extended data table 1. Dimensional values represented on fig. 3 of the main paper fall in the range 15 kyr to 1.62×10^3 kyr.

While only cases with a sufficiently long evolution in this quasi-static stage after maturation of the polygons qualify as belonging to this specific regime, after a sufficiently long period of time, all simulations would lead to a final stage of conductive cooling - this was not yet the case for all the simulations presented here. If bottom heating is introduced (extended data figure 9, 10, 12), a possible outcome is that instead of a final conductive stage, a regime where bottom heating becomes predominant ultimately develops. In this case, a polygonal regime with the reversed topographic pattern may be observed (fig. 1 and extended data figure 10). Although not observed in the high Rayleigh number case shown in extended data figure 12 in spite of a typical duration of nearly 50 kyr, this case should also lead at some point to the reverse pattern. In the case of SP, prolonged periods of minimal or null sublimation-induced buoyancy may thus result either in conductive stages or convective stages with the reverse pattern, depending on the amount of heating from the interior.

A.6 Decay timescale of convection

As shown by climate models, periods of condensation and sublimation alternate on SP. The theory developed in the main paper applies to periods of sublimation while the thermal effect of condensation periods on the surface of SP is unclear at this stage. As a preliminary way to assess the effect of these fluctuations, we assume that the Biot number in eq. 3 of the main text goes to zero during periods of condensation, effectively rendering null the surface heat flow.

As a first application, we considered the evolution of our convecting layer when we suddenly apply a zero heat flux at the top surface. Starting from the last timestep of case #14, the temperature anomalies present in the system drive convective flow even though no buoyancy source persists at the boundaries. The warm regions move upward and cannot get cooled down at the surface, which makes the temperature lateral anomalies below the upper surface larger at first (extended data figure 5), driving convection faster (extended data figure 6). After this transient dynamics, temperature anomalies and the convective velocity decrease exponentially owing to thermal diffusion as shown by extended data figure 6. This allows us to determine an e-folding timescale for suppressing temperature anomalies, which in this case is approximately 147 kyr. The same calculation has been performed for case #15 and lead to an even longer timescale of 168 kyr, owing to the longer wavelength of its planform.

A.7 Case with an intermittent sublimation rate with seasonal variations

If sufficiently long-lasting, periods of net condensation may impede the Archimedian forcing considered in our simulations, as the supply of negative buoyancy to the unstable boundary layer would be absent. Diurnal (6.4 Earth days) variations are too short to affect the thermal state of the nitrogen ice layer but the effects of seasonal fluctuations with a period of 250 Earth years need discussion. To mimic this effect, we ran some calculations where the Biot number fluctuates with positive and negative values, leading to alternative periods of heating and cooling of the surface, while keeping a small but cooling time average. Specifically, the Biot number evolves as

$$Bi = 100 \left(\frac{1}{4} + \frac{3}{4} \cos \left(2\pi \frac{t}{P} \right) \right) \quad (14)$$

with P the duration of Pluto's year. This treatment is not meant to realistically model the physical problem since condensation could happen in the form of a thin frost layer at the surface of SP, which would eventually be incorporated by sintering. Such processes are not

fully captured by our simple boundary condition which is only meant to apply to sublimation periods. Nevertheless, this approach allows us to assess the role of seasonal variations.

We ran a case with this condition with a nominal Rayleigh number $Ra_\infty = 10^7$ and an activation energy in the high end of the range for polygonal regime with constant conditions. The rationale for that choice is that, as seen for the case when the Biot number is suddenly set to 0 (§ A.6), the temperature just below the upper surface increases when the surface heat flow drops to 0. This leads to a decrease in the effective viscosity contrast.

Extended data figure 7 shows the evolution with time of the same diagnostics as on extended data figure 2, with close-ups on the last 5 time periods for each. The nominal viscosity contrast for this case is 3×10^4 but the effective viscosity contrast reaches a value of order 1400 at the end of the run. As can be clearly seen on the figure, the overall evolution is similar to that of constant boundary condition, with short-period small-amplitude fluctuations, except for the surface heat flow. The effective Rayleigh number and viscosity contrast place this case in the polygonal regime on figure 2 and, indeed, the last snapshot of surface topography and mid-depth temperature (extended data figure 8) confirms that.

Nevertheless, the polygonal size is significantly smaller than that for constant boundary conditions in the same area of the regime diagram. Several reasons can be invoked for this observation. Firstly, the periods of condensation as modeled by a negative Biot number may lead to a delay in maturation of the largest scale patterns. Secondly, the alternating periods of surface cooling and accumulation of heat below the upper surface leads to the development of a complex rheological structure of the boundary layer. This could make the regime diagramme for time-dependent boundary conditions a bit different from the one obtained for a constant one. This question will deserve more attention in the future, once a more complete theory accounting for condensation periods has been developed.

A.8 Effect of bottom heating

According to our interpretation of the convective pattern (i.e. caused by surface cooling equivalent to internal heating), net sublimation rates must be sufficient for the associated surface heat flux to exceed the basal heat flux. While not included in our reference calculations, the latter certainly contributes to SP’s heat budget and is classically estimated to a few milliwatts per square meter⁴. The dominant contribution to bottom heating is most probably the heat produced by radiogenic decay in Pluto’s “rock” core. The radiogenic content of Pluto’s forming materials is uncertain, however, as meteorites analyzed on Earth do not sample such distant origins. Assuming a CI chondritic material (heat production at present, $3.44 \times 10^{-12} \text{ W kg}^{-1}$), consistent with the bulk density corresponding to the PF2 model proposed by McKinnon et al.³⁹, the purely radiogenic heat flux emanating from a 890-km core would be 1.8 mW m^{-2} at the base of SP. Growing evidence suggests however that a significant amount of carbonaceous organic matter is probably involved in the building blocks of all planetary bodies beyond the snow line⁴⁰. The likely presence of organics in Pluto’s core bulk composition, consistent with inferences on cometary material would lower the estimates of radiogenic heating⁴¹: a model with 45 wt % organics for Pluto’s core inspired by estimates for comet 67P/Churyumov-Gerasimenko^{42,43}, also providing the appropriate bulk density for Pluto, yields a twice smaller radiogenic power as the rock core would then only be 710 km in radius, enveloped by a 130-km thick layer of organics⁴¹. Other contributions to the basal heat flux in SP are secular cooling/heating of the various layers (“rock core”, potential ocean, water ice mantle). To our knowledge, all thermal evolution models proposed for Pluto assume a chondritic composition for the rock core^{44,45}. Although large portions of Pluto’s evolution first involves heating of

the interior in such models, these favor at present a global cooling of the layers so that heat delivered at the base of SP would slightly exceed the radiogenic value. Note that if part of the potassium (approximately half the power radiogenic power in CI chondrites) leached into the hydrosphere, the heat-buffering role of the highly viscous rock core could be lessened. Similarly, latent heat effects could contribute: if an ocean is present and currently freezing, or if a clathrate layer is currently thickening at the interface between the ocean and the ice crust⁴⁵, the amount of heat delivered at the base of SP would exceed the radiogenic value. At present, heat sources/sinks associated to secular cooling/heating or latent heat nevertheless constitute secondary contributions in available thermal histories for Pluto, altering the radiogenic budget by only a few tenths of milliwatts per square meter. Among proposed thermal evolution models, the only exception could be associated to the ocean heating phase subsequent to the initial growth of a clathrate layer, owing to the insulating power of the latter: according to Kamata *et al.* [45], this would approximately correspond to a 1 mW m^{-2} reduction of the flux supplied at the base of SP (50 K in about 1 Gyr). Whether this effect could be delayed up to the present time remains to be investigated.

In order to assess the effect of heating from the bottom in our models, we ran two calculations similar to case #14 but including an imposed bottom heat flux equal, in dimensionless units, to 1 (extended data figure 9) and 5 (extended data figure 10), corresponding to dimensional values $q_{bot} = 0.26 \text{ mW m}^{-2}$ and $q_{bot} = 1.3 \text{ mW m}^{-2}$, respectively, using the same values as in the main paper for scaling (note that this scaling of our dimensionless values is rather uncertain, a variability of at least a factor 2 can be envisaged). According to the above analysis, these two values nevertheless constitute plausible end-members of the actual heat flux entering the base of SP. Extended data figure 9 shows that the lower value of the bottom heat flux leads to a polygonal pattern that is compatible with the observations. However, for the larger value (extended data figure 10), the convection pattern first assumes a polygonal pattern with a small wavelength but before the end of the maturation stage leading to larger cells in case #14, it transitions to a reverse pattern with high topography regions at the sides of polygons. Considering these two specific simulations, two possible conclusions are that either the bottom heat flux entering SP must be smaller than usually assumed on the basis of chondritic heating and thermal evolution models, or that our mechanism is not applicable to SP. In this latter case, an alternative, unknown, mechanism would still be required to explain the topographic lows at polygons' edges. Note however that our investigation of the regime diagram in Fig. 2 does not provide any bounds on the extent of the polygonal regime. In particular, cases with higher Rayleigh numbers can be expected to fall within this regime. In order to maintain admissible values for the surface viscosity, the viscosity contrast is also required to be larger. Hence, either the activation energy assumes a value larger than that reported for the Newtonian creep or other ingredients such as grain size variations contribute to the viscosity contrast (cf. A.3.2). We have performed a supplementary simulation (extended data figure 12) for such a case that indeed belongs to the polygonal regime when a null bottom heat flux is prescribed (extended data figure 11). Owing to an enhanced vigor, the surface convective heat flux is larger (about five times that for case # 14). As a consequence, a second simulation with a dimensionless bottom heat flux equal to 5 corresponding again to $q_{bot} = 1.3 \text{ mW m}^{-2}$ for the reference scaling (extended data figure 12) now still remains in the appropriate regime, exhibiting a topographic pattern similar to SP. Note that these last two calculations have been run with an aspect ratio twice the other cases to allow the large scale pattern to develop. A complete coverage of the three-dimensional $(Ra, \eta_{max}/\eta_{min}, q_{bot})$ regime diagram is out of the scope of the present study. We nevertheless conclude from this example that a large bottom heat flux, up to the classically assumed value for Pluto, can in principle yield the appropriate regime driven by sublimation,

as long as surface cooling is sufficient.

In conclusion, our proposed mechanism for the convective dynamics in SP requires that the surface cooling be predominant over the heat flux at the bottom of the layer due to radiogenic heating in the rocky core and secular cooling/heating of the interior (q_{bot}). The maximum admissible bottom heat flux essentially depends on the unknown viscosity of the bulk of the nitrogen ice layer: if this value is in the range 10^{14} Pas to 10^{15} Pas as is the case for most simulations displayed in Fig. 3 in agreement with the nominal activation energy for a Newtonian creep, then q_{bot} is smaller than commonly anticipated, i.e. it requires the presence of a significant fraction of organic matter in Pluto’s interior and/or a non-canonical thermal evolution ; if the viscosity of “warm” nitrogen ice is smaller, i.e. 10^{12} Pas to 10^{13} Pas, then larger values of q_{bot} , such as the ones generally assumed (typically 2 mW m^{-2}), can be accommodated in the appropriate polygonal regime.

B Data availability

All results necessary to produce the figures are available in the zenodo repository <https://doi.org/10.5281/zenodo.5511744>.

C Code availability

The convection code StagYY is the property of Paul J. Tackley and Eidgenössische Technische Hochschule (ETH) Zürich. Researchers interested in using StagYY should contact P.J.T. (paul.tackley@erdw.ethz.ch). Scripts for the treatment of results and drawing of figures have been written in Python (<https://www.python.org/>) using the StagPy package (<https://github.com/StagPython/StagPy>) in the zenodo repository, along with the data.

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Extended data table 1:

Input parameters and output diagnostics.

Input parameters (Rayleigh number Ra , activation energy for the viscosity E_η) and output diagnostics for the last snapshot: effective viscosity contrast, number of cold plumes N_{plu} , number of hot connected components (polygons in relevant cases) at the surface N_{hot} , ratio R_v of horizontal velocity (RMS) at the surface to the maximum value, horizontal velocity (RMS) at the surface v_h , median size of hot connected components L_{med} , amplitude Δh and RMS $RMS(h)$ of surface topography. τ_p is the dimensionless time needed to establish the polygonal regime, as determined by the same criteria as for the regime diagram, when relevant. Missing data for N_{hot} and L_{med} are for cases in the stagnant or sluggish lid regimes for which these diagnostics have little relevance. All the output diagnostics provided here are those obtained at the end of all runs, after the maturing of the convective pattern.

Extended data figure 1:

Topography slope.

Slope of topography for cases # 14 (left) and 15 (right), with the mean value written in the upper left corner.

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Extended data figure 2:

Time evolution of output diagnostics for case # 14.

Evolution with time of the surface heat flux (a), the mean temperature (b), the RMS velocity (c), the effective Rayleigh number (d) and viscosity contrast (e) in the case of figure 2(b,e) of the main text. The first three quantities have been rendered dimensional using the nominal values of the parameters, see table 1 of the main text.

Extended data figure 3:

Effective temperature as function of effective Rayleigh number for case # 14.

Evolution of the dimensionless temperature as function of the internal heating Rayleigh number, using secular cooling as effective internal heating source (see methods), for case # 14. The dashed line shows a guide to the eye for the expected scaling law in steadily cooling situation. The circled numbers correspond to snapshots, some being presented on extended data 4, the red ones being in the polygonal regime, which is first established at snapshot 18.

Extended data figure 4:

Pattern maturation for case # 14.

Four snapshots (# 2, 10, 18 and 30) of the surface topography (left) and mid-depth temperature anomaly (right) for case # 14, each associated with a circled number on extended data 3.

Extended data figure 5:

Temperature profiles during decaying convection.

Evolution of the horizontal minimum (blue), mean (red) and maximum (green) temperature profiles following the application of a zero heat flux at the upper surface of an established convecting system, case #14.

Extended data figure 6:

Decaying time-scale of convection.

Time evolution of the temperature anomalies (a, b) and the RMS velocity (c) after the surface heat flow has been set to zero. (a) shows the vertical mean of $T_{max}(z) - T_{min}(z)$. (b) shows the RMS of $T - \bar{T}(z)$, with $\bar{T}(z)$ the horizontal mean of temperature. The exponential fit has been performed on values for time ≥ 55 kyr.

Extended data figure 7:

Time evolution of output diagnostics for a time-varying boundary condition.

Time evolution of the same diagnostics as in extended data 2 for a time varying boundary condition at the surface. The insets in each panel shows a zoom on the last 5 periods of the oscillations.

Extended data figure 8:

Convection pattern for a time-varying boundary condition.

Surface topography and mid-depth temperature anomaly at the end of the time varying run presented on extended data 7.

Extended data figure 9:

Evolution of the layer with an imposed bottom heat flux $q_{bot} = 0.26 \text{ mW m}^{-2}$.

Panel (a) shows the evolution of the surface and bottom heat fluxes, (b) the mean temperature, (c) the RMS velocity, (d) the effective Rayleigh number, (e) the effective viscosity contrast and the bottom ones, snapshots of the topography at times written on their respective upper left corners.

Extended data figure 10:

Evolution of the layer with an imposed bottom heat flux $q_{bot} = 1.3 \text{ mW m}^{-2}$.

Panel (a) shows the evolution of the surface and bottom heat fluxes, (b) the mean temperature, (c) the RMS velocity, (d) the effective Rayleigh number, (e) the effective viscosity contrast and the bottom ones, snapshots of the topography at times written on their respective upper left corners.

Extended data figure 11:

Evolution of the layer for $Ra_\infty = 10^9$ and $R_\eta^\infty = 10^4$ with a zero imposed bottom heat flux.

Panel (a) shows the evolution of the surface and bottom heat fluxes, (b) the mean temperature, (c) the RMS velocity, (d) the effective Rayleigh number, (e) the effective viscosity contrast and the bottom ones, snapshots of the topography at times written on their respective upper left corners.

Extended data figure 12:

Evolution of the layer for $Ra_\infty = 10^9$ and $R_\eta^\infty = 10^4$ with an imposed bottom heat flux $q_{bot} = 1.3 \text{ mW m}^{-2}$.

Panel (a) shows the evolution of the surface and bottom heat fluxes, (b) the mean temperature, (c) the RMS velocity, (d) the effective Rayleigh number, (e) the effective viscosity contrast and the bottom ones, snapshots of the topography at times written on their respective upper left corners.