ESS2222H

Tectonics and Planetary Dynamics
Lecture 4
Tectonic Evolution of the Terrestrial Planets

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Review of Lecture 3

**Spherically Averaged Earth Structure**

\[
\frac{d\rho}{dr} = \left( \frac{\partial \rho}{\partial P} \right)_s \frac{dP}{dr} + \left( \frac{\partial \rho}{\partial s} \right)_P \frac{ds}{dr} \quad \text{Williamson and Adams}
\]

\[
\begin{align*}
\frac{d\rho(r)}{dr} &= -\frac{\rho(r)g(r)}{\phi(r)} \\
\frac{1}{r^2} \frac{d}{dr} \left( r^2 g(r) \right) &= 4\pi G \rho \\
\frac{dm}{dr} &= 4\pi r^2 \rho(r)
\end{align*}
\]

**Boundary conditions:** Earth’s mass, Earth’s moment of inertia

**Bullen’s Earth Model A, B (1936, 1940)**

Six-layer model – Near surface phase transitions predicted- Discrepancies in D” can not be explained by these preliminary models.

**PREM Model of Dziewonski (1981)**

Near surface phase transitions predicted but not deep mantle Pv-pPv - Similar difficulties
Pv-pPv Deep Mantle Exothermic Phase Transition

To a large extent could explain the deep mantle D” – discontinuity properties including:

a) Variations in $\rho$, $V_s$, and $V_\phi$

b) $V_s$ , $V_\phi$ anti-correlation

c) Large reduction in $V_s$ and $V_P$ in ULVZ’s

d) Large values of Poisson ratio

\[ \nu = \frac{(\frac{V_P}{V_s})^2 - 2}{2 \left[ (\frac{V_P}{V_s})^2 - 1 \right]} \]

Slab Stagnation by the Endothermic Phase Transition
The Thermal and Tectonic Evolution of the Planets

Mars

**Plate Tectonics**

Active plate tectonics is **unique** to the **Earth**. Plate tectonics occurred on Mars **early** in its evolution. Mars is significantly **smaller** than the Earth and Venus and, for this reason, its **tectonic** and **volcanic** evolution would be expected to be different. Mars is believed to be largely **tectonically quiescent** (dead planet), because:

1. Due to the **large surface area to volume ratio** more heat has been lost and the interior has cooled (no convection).
2. **Crustal differentiation** on Mars has been more efficient and a large fraction of the incompatible heat-producing elements are now near the surface where heat can be lost by **conduction**.

Martian activities in estimated to have **stopped 3.5 billion** year ago, with no volcanic activity and magnetic field since then. Today, It may have **molten outer core** but with **no convection**.
The Late Heavy Bombardment (LHB), or Lunar Cataclysm

This is a hypothesized event thought to have occurred approximately 4.1 to 3.8 billion years (Ga) ago (corresponding to the Neohadean and Eoarchean eras on Earth). During this interval, a large number of asteroids have collided with the early terrestrial planets in the inner Solar System, including Mercury, Venus, Earth, and Mars.
The Thermal and Tectonic Evolution of the Planets

Mars

Hemispheric Dichotomy

The most striking global feature of the Martian surface is its hemispheric dichotomy. This could be related to the dominance of a low degree spherical harmonic pattern of mantle convection early in Mars’ geologic history or, possibly, with a period of plate tectonics.
A low degree spherical harmonic pattern of mantle convection
The spinel–perovskite or olivine–spinel transformation in the Martian mantle could enforce a convection mode dominated by a single plume.
**The Thermal and Tectonic Evolution of the Planets**

**Mars**

### Surface Ages

The **density of impact craters** can be used to specify **relative ages** of the surface (by counting the number of visible craters: a higher number and density of craters indicates older terrain) (Tanaka, 1986).

Southern hemisphere (heavily cratered): **Older**

Northern hemisphere (low-lying volcanic plains): **Younger**

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**Martian Epochs and Absolute-age Ranges Based on Hartmann–Tanaka (HT) and Neukum–Wise (NW) Ages, Which Represent the Two Different Time Scale Models (Tanaka et al., 1992)**

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Absolute-age Range (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HT</td>
</tr>
<tr>
<td>Late Amazonian</td>
<td>0.25–0.00</td>
</tr>
<tr>
<td>Middle Amazonian</td>
<td>0.70–0.25</td>
</tr>
<tr>
<td>Early Amazonian</td>
<td>1.80–0.70</td>
</tr>
<tr>
<td>Late Hesperian</td>
<td>3.10–1.80</td>
</tr>
<tr>
<td>Early Hesperian</td>
<td>3.50–3.10</td>
</tr>
<tr>
<td>Late Noachian</td>
<td>3.85–3.50</td>
</tr>
<tr>
<td>Middle Noachian</td>
<td>3.92–3.85</td>
</tr>
<tr>
<td>Early Noachian</td>
<td>4.60–3.92</td>
</tr>
</tbody>
</table>

The **Hesperian** is a geologic system and time period on the planet Mars characterized by **widespread volcanic activity** and **catastrophic flooding** that carved immense outflow channels across the surface.
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Mars

**Tarsis Bulge**
The Tharsis uplift and the associated great shield volcanoes on Mars can be attributed to pressure-release melting in a single large plume within Mars.

**Valles Marineris**
Another major question concerning Mars is the origin of the Valles Marineris canyon system (Mariner Valley). It has been suggested that Valles Marineris is a large tectonic "crack" in the Martian crust (formed by the crust thickening). The canyon system and associated outflow channels developed mainly during the Hesperian Period. The graben systems in and near the Tharsis region are likely the result of stresses generated by the Tharsis load. The system is ~ 4000 km long and reaches ~7 km in depth.
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Mars

The older regions on Mars are isostatically compensated. The younger region are usually only partially compensated.

Mars free-air gravity map (Red: gravity high; Blue: gravity low)
Cumulative surface area, in percent, younger than $\tau$ as a function of the age $\tau$ for the Earth, Venus, Mars, and the Moon. For the Earth, crustal ages younger than 125Myr are principally oceanic (oc), whereas older crust is entirely continental (cc). For Mars and the Moon the older highlands are distinguished from the younger, lower-lying volcanic plains. For Venus and Mars the ages are based solely on crater counts, so that relative ages are reasonably accurate but absolute ages are subject to considerable error.
Differentiation

The major evidence for an initially hot and differentiated Mars is the acceptance of Mars as the parent body of the SNC meteorites (Becker and Pepin, 1984; Bogard et al., 1984; McSween, 1985).

The old age (≥4 Gyr) of the southern hemisphere highlands suggests early crustal differentiation, and the magnetization of this ancient southern hemisphere crust (Acuna et al., 1998, 1999).

Early Core Formation

Early Mars was similar to the larger terrestrial planets Venus and Earth, whose cores formed early as a consequence of high accretional temperatures. The U/Pb isotopic composition of SNC meteorites (Shergotty (India), Nakhla (Egypt), and Chassigny (France), the locations where these meteorites were found) requires core formation at about 4.6 Gyr ago (Chen and Wasserburg, 1986).

Early core formation in a hot Mars is further supported by the discovery of remanent magnetization in the ancient crust of the southern hemisphere highlands (Acuna et al., 1999; Connerney et al., 1999).
U/Pb dating
The method is usually applied to zircon (ZrSiO$_4$). This mineral incorporates uranium and thorium atoms into its crystal structure, but strongly rejects lead when forming. As a result, newly-formed zircon deposits will contain no lead, meaning that any lead found in the mineral is radiogenic. Zircons are both ubiquitous in the Earth’s crust and are able to survive processes of erosion, transport, and even high-grade metamorphism, they provide exquisite records of tectonophysical processes.
Crustal Differentiation
Reese et al. (1999) find that hot early Mars models undergo substantial crustal differentiation within a few hundred million years at the onset of evolution and substantially deplete their interiors of radiogenic heat sources. The rest of the evolution subsequent to crustal formation involves a steady decline of mantle temperature and a thickening of the lithosphere to present values of around 500 km.

Mantle Convection
The persistence of mantle convection in Mars to the present depends on the extent to which the interior has been depleted of radiogenic heat sources by crustal differentiation. Crustal formation is an important influence on planetary thermal history because the process of forming the crust by magmatism and volcanism removes heat-producing radiogenic elements from the mantle and concentrates them in the crust.
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Mars

**Early vigorous Convection**
As a result of **accretional** heating and **core formation** essentially **contemporaneous** with planetary formation, the early history of Mars was characterized by **high internal temperatures**, a **vigorously convecting mantle**, and **high surface fluxes of heat and magma**.

Outgassing contributed to an early atmosphere, and widespread magmatism may have helped trigger the release of subsurface water and large scale floods.

**Fast Cooling**
Parameterized convection models indicate, however, that on a time scale of only a few 100Myr the mantle convective engine slowed, as primordial interior heat was lost and as radioactive heat production decayed or was **concentrated into the shallow crust**. **Rapid interior cooling** led to a globally **thick lithosphere** and was accompanied by global contraction, recorded in the pervasive formation of wrinkle ridges now preserved on ancient geologic units. The last 3.5 Gyr of Martian history was marked, in contrast, by slow cooling and by the concentration of volcanic and tectonic activity in ever more limited regions.
Mantle temperature versus time from the Martian thermal history model of Schubert and Spohn (1990).

Heat flux from the mantle as a function of time for a model Martian thermal history (after Schubert and Spohn, 1990).

Thickening of the lithosphere with time during the model thermal evolution of Mars (after Schubert and Spohn, 1990).
**Single Plate Planet**

Mars is a *one-plate planet* with a lithosphere that has *thickened* with time during the course of its thermal evolution (Solomon, 1978; Schubert et al., 1979). *Stagnant-lid* convection is a *plausible state* for the Martian mantle given that Mars is a one-plate planet with a thick lithosphere (Reese et al., 1998, 1999).

**Heat Flux**

Based on the Martian thermal history model of Schubert and Spohn (1990) the present *mantle heat flow* in these models is about *30mWm⁻²*. The *present surface heat flow* is about *40mWm⁻²*. Because of lithosphere thickening and cooling, surface heat flow is approximately *10mWm⁻²* larger than the present mantle heat flow.
Core Dynamo

Mars does not have a magnetic field at present (Acuna et al., 1998, 1999). The southern hemisphere crust must have been magnetized in a magnetic field generated by a dynamo in the molten metallic core of Mars during the first several hundred million years of Martian evolution (Acuña et al., 1999; Connerney et al., 1999). A core dynamo existed for perhaps the first 500Myr of Martian history. The absence of crustal magnetism near large impact basins such as Hellas and Argyre implies that the early Martian dynamo ceased to operate about 4 Gyr ago (Acuna et al., 1999).
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Venus

Size, mass, density of Venus ~ Size, mass, density of Earth

Venusian day is ~117 Earth days (sidereal day)

Venus orbits the Sun every 224.7 Earth days (solar day)

Expected Hypothesis:
The tectonics of Venus would be similar to the tectonics of the Earth and that there would be plate tectonics on Venus. We know that this is not the case and that mantle convection on Venus must be substantially different from mantle convection on the Earth. Indeed two planets are quiet different.

Oceanic rift system and the ocean trenches (surface manifestations of plate tectonics) are missing on Venus. Active plate tectonics is not occurring on that planet (Kaula and Phillips, 1981).

Tectonism and volcanism on Venus requires an understanding of mechanism for heat transfer.
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Venus

a) Thick atmosphere of **Carbon dioxide** – green house effects
b) Surface temperature **475 K** higher than **Earth** (Seiff, 1983)
c) Covered by sulphuric **acid clouds** and droplets and **lightning** (associated with clouds of sulphuric acid), **storms**
d) Some models predict **thin lithosphere** (~40 km), **hot and weak**, without the capability of supporting high topography or large gravity anomalies (Mechanical lithosphere capable to maintain high differential tectonic stresses 10 Mpa-1GPa is 1.5–2 times thinner than thermal lithosphere). The **relaxation** of large impact craters would also be expected **faster** in this model.
e) **However**, Topography and gravity data obtained by Pioneer Venus show serious **inconsistencies** with these expectations. Although the **mean surface roughness** (height to wavelength ratio) on Venus is a factor of 3 or 4 **less** than on the Earth, the **maximum elevations** are **nearly equal** (Pettengill et al., 1980; Bills and Kobrick, 1985; Turcotte, 1987; Ford and Pettengill, 1992). Some models assume a thickness of 200-400 km for the lithosphere.
e) As a one-plate planet, there are tectonic features on Venus. Beta Regio volcanic rise has many of the features of a continental rift on Earth. Alta, Eistla, and Bell Regiones have similar rift zone characteristics (Grimm and Phillips, 1992; Senske et al., 1992).
f) **Aphrodite Terra**, with a length of some 1,500 km, is reminiscent of major continental collision zones on the Earth (compression). **Ishtar Terra** is a region of elevated topography with a horizontal scale of 2,000–3,000 km.
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Venus

g) A major feature is **Lakshmi Planum**, which is an elevated plateau similar to Tibet with a mean elevation of about 4 km.
h) The highest mountain chain on Venus, **Maxwell Montes** in Ishtar Terra is 11 km high. It was formed by processes of compression, expansion, and lateral movement.

http://www.runspect.com/examples/Lakshmi_Planum_Venus.htm
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Venus

**Venus topography**

Tectonic features are present to a limited extent, including linear "deformation belts" composed of folds and faults. These may be caused by mantle convection. Many of the tectonic features are associated with volcanism.

**Three types of rises:**

a) Volcano dominated rises such as the Bell Regio

b) Rift dominated rises, uplifts by rifting and thinning of the lithosphere such as the Beta Regio and the overlying Theia Mons

c) Corona dominated an uplift caused by the gravitational collapse and extension of a magma chamber, and include the Themis Regio

The rises associated with high-density anomalies, indicate a source from mantle plumes beneath the crust that warp and uplift the region.

https://commons.wikimedia.org/w/index.php?curid=27412892
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Venus

**Topography and Gravity Anomaly Correlation**

In most regions topography and gravity anomaly are correlated.
A proposed model for crustal deformation associated with Beta Regio. A region with constant crustal thickness (a) is uplifted by a hot plume (b) that arises because high Rayleigh number convection is time dependent. The crust flows away from the uplift (c), partly because the viscosity of the lower crust is reduced by heat from the plume. Such flow generates rifting on the top of the dome and thrusting where the crust is thickened. When the plume moves or decays and the dome subsides (d), leaving an approximately circular region of thinned crust. The lower crust cools before it can flow back into the depression. (McKenzie, 1994)
FIG. 16. A comparison of two high resolution topographic profiles, and gravity profiles from Fig. 11, for the Pacific, (a) and (b), with (c) profiles across Beta of smoothed topography and gravity from Figs. 13a and b, and of high-resolution topography obtained by gridding the altimetric observations. The scales for the gravity profiles are the same for all three profiles, and the topographic and gravity profiles in (c) coincide if the admittance is 57 mgal km⁻¹.

(McKenzie, 1994)
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**Venus**

**Corona Formation**

Coronae are formed when plumes of rising hot material in the mantle push the crust upwards into a dome shape, which then **collapses** in the centre as the molten magma cools and *leaks out at the sides*, leaving a crown-like structure: the corona.

The near circular trough of the *Artemis chasma* has a diameter of 2100 km. The concentric features outside the chasma (a deep, steep-sided depression) are attributed to **normal faulting** associated with *lithospheric flexure* similar to that occurring seaward of subduction zones on the Earth.
Venus is a single plate planet. Using statistical methods and counting the number of impact craters the age of Venus is estimated to be ~ 500 Myr, postulating that a global resurfacing event occurred on Venus about 500 Ma (Schaber et al., 1992).

More recent studies of cratering on Venus that account for atmospheric deceleration and flattening of impactors place the resurfacing somewhat further back in time at about 750 Ma (McKinnon et al., 1997). The atmosphere of Venus is much denser than the Earth and is composed of 96.5% carbon dioxide, 3.5% nitrogen, and traces of other gases, most notably sulphur dioxide. The surface temperature and pressure are ~740 K and 93 bar (9.3 MPa), respectively.
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Venus

Convection

Certainly mantle convection occurs in Venus. So why the global tectonics is absent in Venus?

The absence of global tectonics is possibly related to its hot and dry conditions. In the case of Earth water content of the lithosphere play an important role in plate tectonics.

Heat Transfer

How the internal heat generated by radiogenic isotopes is lost to the surface of Venus?

a) Conduction
b) Volcanism
c) Periodic (500-750 Myr) lithosphere overturn

After a subduction event (lithosphere overturn), the lithosphere gradually thickens until its gravitational instability drives another global subduction event.
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Venus

The Absence of Magnetic Field
Venus may have a molten core, but because it spins very slowly (once every 243 Earth days) it does not generate a magnetic field.

Three requisites for a dynamo to operate:
1) Electrically conductive fluid medium
2) Kinetic energy provided by planetary rotation
3) A convective motions within the fluid
Isostasy

\[ P = \frac{F}{S} \]

Body force = \( m g = \rho V g = (\rho y \delta A)g \)

Surface force = \( PS = \sigma_{yy} \delta A \quad (P \equiv \sigma_{yy}) \)

\[ \sigma_{yy} = \rho gy \]

The weight of displaced water exactly equals the decrease in weight of the block.
Airy Model
According to the Airy model, lithospheric blocks all have the same density but different thicknesses; the thicker blocks have their top surfaces higher and their lower surfaces deeper than thinner blocks, and so higher ground is where the lithosphere is thicker.

\[(\rho_{\text{lith}}h_{\text{lith}} + \rho_{\text{asth}}h_{\text{asth}})_A = (\rho_{\text{lith}}h_{\text{lith}} + \rho_{\text{asth}}h_{\text{asth}})_B\]

Pratt Model
The Pratt model is more complex: Blocks all float to the same depth but have different densities; higher blocks are composed of less dense rocks. The weight equation becomes:

\[(\rho_{\text{lith}}h_{\text{lith}})_A = (\rho_{\text{lith}}h_{\text{lith}})_B\]
**Isostasy**

### Airy’s Hypothesis

\[
\begin{align*}
\sigma_{yy} &= \rho_m g b \\
\sigma_{yy} &= \rho_c g h \\
\rho_c g h &= \rho_m g b \\
b &= \rho_c h / \rho_m \\

h - b &= (1 - \rho_c / \rho_m)
\end{align*}
\]
Pratt’s Hypothesis

A mountain height $h_1$ is underlain by low density material, density $\rho_1$

$$\rho_1 = \rho_u \left( \frac{D}{h_1 + D} \right)$$

$\rho_u D = \rho_1 (h_1 + D)$

$\rho_u D = \rho_w d + \rho_d (D - d)$

Ocean basin depth, $d$, is underlain by a high density material, density $\rho_d$

$$\rho_d = \frac{\rho_u D - \rho_w d}{D - d}$$
Airy Hypothesis or Pratt Hypothesis?

Which model actually occurs? First, you need to realise that these are not the only possible models, just extreme ones. Blocks might differ in both thickness and density, in various combinations.

For a given location we must ask ourselves

• Is there isostatic equilibrium?
• Which process is operating?
• Is it a combination of the two?

Pratt and Airy are end members
Observations subject to extraneous effects unrelated to subsurface geology

1) Latitude correction
2) Free-air correction
3) Bouguer correction
4) Terrain correction

Latitude Correction

Variation in $g$ due to the spheroid

$$g_\lambda = g_e(1 + \alpha \sin^2 \lambda + \beta \sin^4 \lambda) \quad m/s^2$$

where

$\lambda$: the latitude,

$g_e$: the gravitational acceleration at the equator

$g_e = 9.7803185 \quad m/s^2$

$\alpha = 0.005278895$

$\beta = 0.000023462$
Free-air Correction

Accounts for an elevation ($h$) correction. A gravity measurement was made at an elevation $h$, not at sea level.

$$F = G \frac{M_E m_S}{R_E^2} \Rightarrow g = G \frac{M_E}{R_E^2}$$

The gravity at elevation $h$ above sea level is approximated by

$$g = g_0 \left(1 - \frac{2h}{R_E}\right), \quad g_0 = g_\lambda \text{ at sea level}$$

The free air correction:

$$\delta g_F = g_0 - g_h = \frac{2h}{R_E} g_0$$

Note that gravity decreases with distance from the center of the Earth ➔ The free-air correction is therefore added
Free-air Anomaly

A gravity anomaly: The difference between a theoretical and observed value

The free-air anomaly is calculated by correcting an observation for expected variations due to:
1) The spheroid
2) Elevation above the spheroid (the geoid, or the sea level)

Then the free-air anomaly is:

\[ g_F = g_{obs} - g_\lambda + \delta g_F \]
\[ g_F = g_{obs} - g_\lambda + \frac{2h}{R_E} g_\lambda \]
\[ g_F = g_{obs} - g_\lambda \left(1 - \frac{2h}{R_E}\right) \]
Bouguer Correction

Accounts for rock thickness between observation and sea level.

Treat the rock as an **infinite horizontal slab**, the Bouguer correction is:

\[ \delta g_B = 2\pi G \rho h \]

This additional slab of rock between the observation point and sea level causes an additional attraction.

→ The **Bouguer correction** should be **subtracted** from the observation.
Terrain Correction

If Bouguer correction is inadequate, also use terrain correction (deviations of the surface from an infinite horizontal plane)

Both use elevation differences between station and surround
Bouguer Anomaly

Apply all the corrections:

\[ g_B = g_F - \delta g_B + \delta g_T \]
\[ g_B = g_{obs} - g_\lambda + \delta g_F - \delta g_B + \delta g_T \]

With the Bouguer anomaly:

- We have \textbf{subtracted} theoretical values for the \textit{latitude and elevation}
- We have \textbf{removed} the rock \textbf{above sea level} so the anomaly represents the density structure of material below sea level
- This is comparable to the free-air anomaly over the oceans and both have been corrected to sea level
Anomalies of a Sphere and a Horizontal Cylinder

Assuming the cylindrical anomaly is infinite in length

\[ g = \int G \frac{dm}{r^2} dr \]

\( m_2 = 1 \)
Gravity Anomalies

Example:

\[ \delta g = G \frac{\Delta m}{d^2} = \frac{G}{d^2} \frac{4}{3} \pi r^3 \delta \rho \]

\[ \delta g = G \frac{\Delta m}{d^2} = \frac{G}{d^2} \frac{4}{3} \pi r^3 \delta \rho \]

\[ \delta g = 1.048 \times 10^{-6} \text{ m/s}^2 \]

\[ 1 \text{ mGal} = 10 \text{ g.u.} = 10^{-5} \text{ m/s}^2 \approx 10^{-6} \text{ g} \]

\[ \delta g \approx 1 \text{ mGal} \]
Transformational Superplasticity

Mechanisms responsible for transformational superplasticity:

a) The reduction in cohesion between the atoms as they move into new positions in a new lattice as the material changes phase (Lozinsky and Simenova, 1959; Underwood, 1962).

b) Some other works link the phenomenon to developing internal stresses due to the transformational volume change (Lehr, 1956b; de Jong and Rathenau, 1961a,b) which is widely accepted and its predictions have been verified in a number of cases.

This phenomenon has been identified as pseudo-creep process (Greenwood and Johnson, 1965, Roberts and Cottrell, 1956) where small stresses insufficient to sustain plastic flow, are able to deform a material in which an internal stress system exists.
Cartoon of the grain geometry evolution during a **solid–solid phase transformation** involving a density change. Higher-density B-phase grains (black) grow at the corners of less-dense A-phase grains (grey). In time $dt$ the old phase loses the same mass as the new phase gains, and the entire aggregate collapses by the volume $dV$ [white gaps in (b) or white area in (c)]. The grains supporting the framework (here the A phase) change shape: the A–A borders move inwards, and the A–B interfaces move outwards to preserve continuity [compare (b) and (c)]. The deviatoric deformation is related to the macroscopic dilatation of the entire sample. (The white line in (c) repeats the geometry in (a))
Aseismic region is attributed to the superplasticity