PLANETARY EVOLUTION: COMPARISON OF THE TECTONICS OF THE ROCKY AND ICY PLANETARY BODIES

E. Illés-Almár
Konkoly Observatory Budapest, H-1525 Box 67, Hungary

Comparing the thermal history of planetary bodies of different composition Holba and Lukács [1] in their simple model investigated the evolutionary track of planetary bodies containing different ices. Their results can be summarized as follows. A planetary body containing cca. 50% water and 50% rocky material (taking into account only radiogenic heating) can be in the same evolutionary stages if it has a radius of about 2600 km as the rocky Earth. Taking ammonia instead of water the appropriate radius will be 2100 km, or metan instead of water 1200 km. The authors did not calculate the evolutionary stages for mixtures of ices.

Four planetary bodies can be found near the above sizes in the real Solar System: Ganymede and Titan of radii ~2600 km within the water-ice zone (Titan can be even younger than the Earth because of the higher ammonia content) and Triton and Pluto of radii ~1200 km within the metan-ice zone (Triton can also be younger than the Earth having larger radius than 1200 km).

Two of the four planetary bodies, however, can not be used for comparison as we have no information about the level of their activity. Titan has a thick atmosphere with smog in it, so its surface could not be mapped, and no planetary probe has visited Pluto up till now. But the mutual eclipses of the Pluto-Charon binary system made it possible to scan their surfaces. So it is known that they are not similar: the surface of Charon contains water-ice while that of Pluto metan-ice [2]. It has been determined further that Pluto now has an atmosphere and polar caps.

What level of geological activity can be observed on the surfaces of the crusty planetary bodies in the Solar System? We can distinguish three kinds of surfaces:

1./ There is no trace of any kind of geological activity. The surface shows up only impact craters, that means, the body was only a passive target of impacts throughout its lifetime, as for example our Moon, Callisto (Fig. 1.A) or Rhea.

2./ There is some trace of geological activity, but it ceased to exist sometime in the past as indicated by the presence of impact craters on the regenerated part of the surface as in the case of Mars (Fig. 2.B,C), Ariel, Enceladus (Fig.2.A). From the number of craters it can be assessed how long ago the activity has stopped.

3./ If almost no impact craters can be observed on a surface it means tha either the activity is continuing even today – as in the case of Earth, Io (Fig. 3.A), and Triton (Fig. 3.B) – or the activity has stopped only recently, as in the case of Venus (Fig. 4.A) and Europa (Fig. 4.C).

The table contains in five groups all crusty planetary bodies with diameters greater than 200 km. The groups are arranged according to their distances from the Sun. Within each group the bodies are arranged according to their sizes because simple geophysical models suggest that in the case of quasi identical composition the greater is the body the longer lasts its time of activity, that is the younger is its surface.

The first group contains the rocky planetary bodies. Io is included because of its composition although it is orbiting in the Jovian system and is not even the largest one of the Galilean moons. The second group is formed by the other three members of the Jovian system containing ~50% rocky material and ~50% water ice.
The third group is formed by the satellites of the Saturnian system, where besides water ice the ammonia ice can also be an important constituent.
The fourth group is formed by the large satellites of the Uranian system where besides water and ammonia ices metan ice is also present.
In the fifth group besides the above mentioned ices the nitrogen ice plays also an important role.

Excluding Io the rocky bodies are more or less fitting to the model, only the high level of volcanism on Venus (Fig. 4.B) is a problem. Does it mean that Venus is more active than the Earth, or it represents only an other style of tectonism (buble tectonism [3])? In any case the size and very probably the composition of Venus and Earth are so similar, that a very different level of geological activity is not likely. There was one case, however, when the scientific community was surprised from such a phenomenon: on the surface of Ganymede and Callisto (Fig. 1.A,B) – in spite of their very similar position, size and composition – a very different level of geological activity has been found.

The picture is more complicated in the satellite systems of the giant planets than in the case of the rocky bodies. In the separate groups the most active bodies are generally not the largest ones! For example besides the above mentioned cases of Ganymede and Callisto the smaller Io is a more active member of the Jovian system; even in the group of the rocky bodies the tiny Io has an outstanding virulent activity.

The fact that the most active members of the Jovian, Saturnian and Uranian satellite systems are not the largest ones points to the fact that the Holba-Lukács model can be used only for the comparison of more or less isolated bodies. In systems of satellites namely the orbital energy can be a heat source through tidal dissipation of even comparable magnitude to the radiogenic heating therefore the activity-order based on the size of the bodies can be perturbed.

<u>The tidal heating can be longlasting or episodic</u> as compared to the lifetime of the Solar System. It is longlasting in the case of the Earth because of the presence of the Moon. Similarly longlasting is in the case of Io because of the forced excentricity of its orbit. For episodic tidal heating an example is the capture-process as in the case of Triton when its orbit became circular [4]. An other example is the resonance-process, when the inclination/excentricity of an orbit changes considerably, as in the case of Enceladus or Ariel. This latter type of tidal heating, moreover, can occur even more than once in the lifetime of a satellite moving in a satellite system.

In the case of episodic tidal heating the rule of the continuously diminishing level of geological activity can turn over as well. Namely, in the life of a satellite such an active period can occur at any time, the consequence of which can be the renewal of the whole or of a part of the surface. The tidal heating, namely, is not necessarily the same in the whole body, so it can cause local phenomena for example local centres of volcanism or tectonism.

In such episodic cases the character of the cooling can change at once; the conduction can change suddenly into convection. Such a sudden conversion could also contribute to the surface dichotomy of Ganymede and Callisto [5].

The above mentioned facts make the two surfaces on which the Holba-Lukács model could be controlled also problematic, because both of them suffer from tidal heating. Nevertheless they are not contradictory to the model, as Ganymede has one of the two surfaces upon which a transform fault can be seen (Fig. 5.A; the other is Enceladus with a diameter of 500 km, Fig. 2.A). On the surface of Triton in the crossing of a pair of fractures, however, a very early stage of the formation of a transform fault can be recognized (Fig. 5.C, [6]), so the surface of Triton can be considered even younger than that of the Earth; plate tectonics is just starting on its surface.

Any case, in the Solar System plate tectonics in a developed form can only be found on the Earth (Fig. 5.B). The existence of plate tectonic movements was previously suspected on the surface of Venus as well, but Magellan results refuted this hypothesis [3]. In the case of Mars the existence of Valles Marineris (Fig. 2.B,C) makes it probable, that once upon a time the formation of a fracture of expansion character (Fig. 2.C) started that could be similar to the oceanic trenches on Earth. The process came to an early end, however, because of the too quick thickening of the crust.

What can be the cause of the exeptional situation on the surface of the Earth? I suppose the cause may be found in the existence of the Moon [6]: on the one hand in the process of its birth, and on the other in the nonsynchronous rotation of the Earth with respect to the revolution of the Moon. Namely, plate tectonics can produce such manyfold traces (Fig. 5.B) on a surface only, if it could go through several cycles. If the velocity of the mantle circulation is too slow compared to that of the cooling and consequently to that of the thickening of the crust, then the splitting of the crust into plates will not occur for a long time. In such a case perhaps an extensional feature – like Valles Marineris (Fig. 2.C) on the surface of Mars – can be observed. Or if the cooling was a little slower, then there was enough time for the forming of one (Ganymede; Fig. 5.A) or two (Enceladus; Fig. 2.A) transform faults before the whole process stopped. The surfaces of the planetary bodies suggest that – except on the Earth – the cooling was everywhere quicker than would be needed to the longlasting operation of the plate tectonic process. Since the Earth is the only planet being in a double planet-system the rotation of which is not synchronized yet, I consider possible that the tidal heating originating from the Moon's orbital motion can – at least partly – compensate the heatloss by cooling and thus helps to keep the crust permanently sufficiently thin but rigid. According to the giant impact theory the Earth got an enormous quantity of impulse by the impact which could help to initiate a quick circulation in the mantle and in the outer core. This could explain why the magnetic field of the Earth is so strong compared with other rocky bodies, making the Earth more similar to the giant planets in this respect. The traces of the impact may remain not only in the pattern and velocity of the mantle/outer core circulation but even in the oscillation of the position/shape of the inner core [7].

The other double planet in the Solar System is the Pluto-Charon pair. In their case the synchronisation is completed already, so contrary to the general opinion I am not expecting the presence of traces of recent geological activity on their surfaces; on the other hand traces of ancient activity yes [8]. The composition of Pluto and Charon are namely so different, that we can expect with good reason that these two planetary bodies came into being in different regions of the solar nebula; so not in company like other regular satellite systems and not from a common material like the Earth and Moon. Very probably they approached later and captured each other with the gravitational assistance of another body (because of their orbital period this third body might be Neptune). Their relative orbits became circular and their revolutions synchronous by the mutual tidal forces. As they are nearer to each other than the Earth and Moon (only 20 with respect to 384 thousand km) and their masses are more similar (mass ratio is 11 with respect to 81) the period of synchronisation caused stronger tidal heating in both of them with possibly high geological activity even on Pluto (because of its composition), and the total synchronisation of the system took place quicker.

But why is Venus active if it has no large moon? It is very probable that its massive atmosphere is responsible for this situation. Not only by its insulating effect slowing the cooling down but also by its runaway greenhouse effect keeping the surface temperature high.

There is another essential point in plate tectonics. Geophysicists consider the existence of water on the surface of the Earth in connection with the presence of plate tectonics very important. They think it helps to slip the plates as a lubricant. The lack of plate tectonics on Venus is usually explained by the absence of water on its surface besides the extremely high surface temperature that makes the crust too plastic to be able to subduct.

Earth is really exceptional with its flowing water on its surface. Although even there is a possibility of control. Namely, on the contrary to the other two icy Galilean satellites of Jupiter, in the case of Europa (Fig. 4.C) H_2O forms a separate layer of ~100 km thickness above the rocky core with a ~10-20 km thick icy crust on it [9]. This ocean is, however, ten times deeper than the terrestrial analogue but because the gravitational acceleration on the surface of Europa is only about a tenth of the terrestrial one, the conditions could be about the same on the floor of the ocean of Europa. It would be interesting to know whether there are features characteristic of plate tectonics; and if there are, whether they are similar to the terrestrial ones. May be radar technics on appropriate wavelength can map the rocky surface of Europa as it did help in the case of Venus through the thick ocean of clouds.

Summarizing the two planetary bodies, Ganymede and Triton, that can be used to control the composition dependent scaling of the size dependent thermal history do not contradict the model. An overview of the whole Solar System, however, points to the fact that the improvement of the model is necessary in two directions. On the one hand it would be desirable to take into account the mixture of ices in the calculations, on the other hand it would be necessary to add the tidal heating to the radiogenic heating. But to carry out such calculations a more precise knowledge of the composition, the inner temperature and resonance situations would be necessary.

References:

1. Holba, A., Lukács, B., On the thermal history of the planetary bodies of the Solar System. See elsewhere in this issue.
2. Buie, M.W., Cruikshank, D.P., Lebofsky, L.A., Tedesco, E.F., Water frost on Charon. Nature, 329, 522-523, 1987.
3. Magellan at Venus. Sci. 252, 247-312, 1991.
4. Weinbruck, U., Spohn, T., Tidal evolution of Triton's orbital inclination. BAAS 24, No 3, 968, 1992.
5. Murchie, S.L., The geologic evolution of Ganymede and its implications for the origin of the Ganymede-Callisto "dichotomy". Paper 4.P.1.2 COSPAR 1988.
6. Illés-Almár, E., Evolution of planetary bodies, in: Evolution: from cosmogenesis to biogenesis, 44-60, eds.: B. Lukács, Sz. Bérczi, I. Molnár, G. Paál. Report KFKI-1990-50/C, Budapest, 1990.
7. Illés-Almár, E. "Remarks..." in: Symmetry and Topology in the Evolution, 28, eds.: B. Lukács, Sz. Bérczi, I. Molnár, G. Paál, Report KFKI-1991-32/C, Budapest, 1991.
8. Illés, E., Plate tectonics in the Solar System, in: Carpathian Basin: Evolutionary stages. 8-10, eds.: B. Lukács, Sz. Bérczi, K. Török. Report KFKI-1993-21/C, Budapest, 1993.
9. Reynolds, R.T., Mc Kay, C.F., Kasting, J.F., Squires, S.W., Europa: The prospect of an ocean. in: Bioastronomy: The next steps, 21-28, ed.: G. Marx, Kluwer Academic Publishers, 1988.

TABLE

composition of the group				
name of the planetary body	**radius (km)**	**density (g/cm^3)**	**age (year) if $< 3 \cdot 10^9$**	**level of activity at any time**
rocky				
Earth	6378	5.52	10^6	AAAA
Venus	6052	5.24	10^8	AAAA
Mars	3393	3.93		A
Mercury	2439	5.43		–
Io	1816	3.57	10^6	AAAA
Moon	1738	3.34		–
rocky + H_2O				
Ganymede	2638	1.93		AA
Callisto	2410	1.83		–
Europa	1563	2.97	10^7	AA
rocky + H_2O + NH_3				
Titan	2575	>1.9		?
Rhea	765	1.33		x –
Japetus	730	1.2		–
Dione	560	1.43		x –
Tethys	530	1.25		x –
Enceladus	251	1.83	10^8	AA
Mimas	197	1.43		–
Phoebe	110	?		?
rocky + H_2O + NH_3 + CH_4				
Titania	805	1.59		x –
Oberon	775	1.50		–
Umbriel	595	1.44		–
Ariel	580	1.65		AA
Miranda	242	1.26		AA?
rocky + H_2O + NH_3 + CH_4 + N_2				
Triton	1352	2.02	10^6	AA
Pluto	1151	2.1		?
Charon	593	1.4		?
Nereid	170	?		?

The number of A-s indicates the level of geological activity visible on the surface. The x indicates a kind of cracking on an otherwise inactive body.

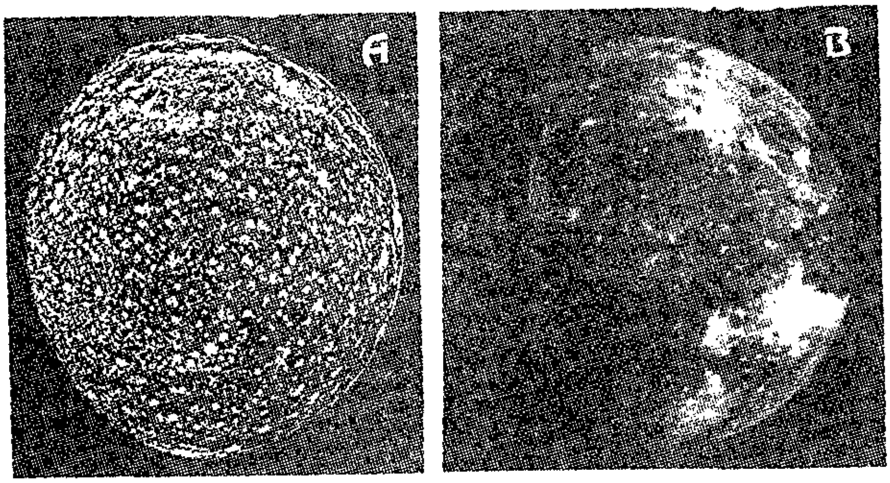
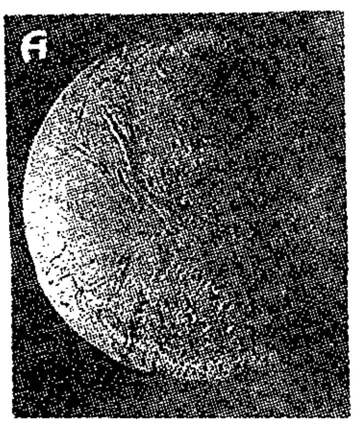
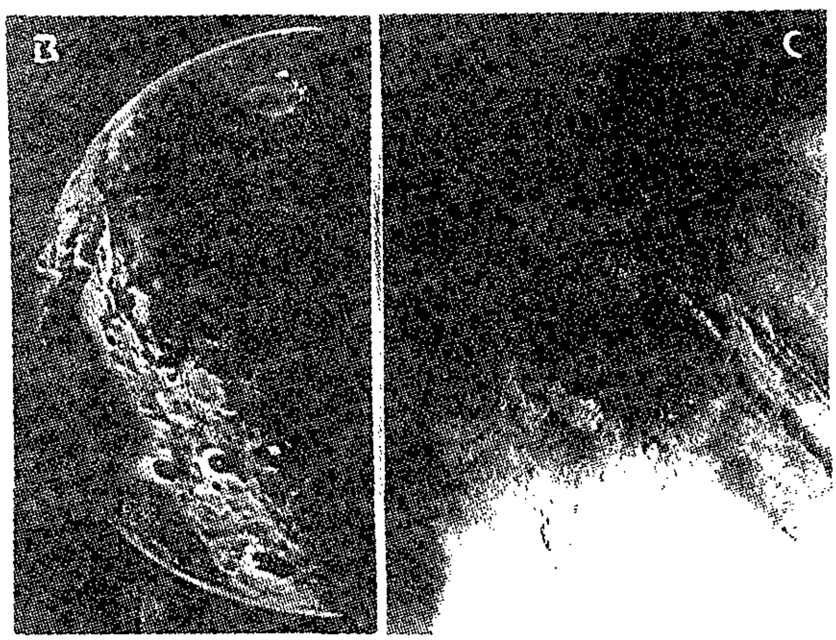


Fig. 1
Callisto (A)
Ganymede (B)

Fig. 2
Enceladus (A)
Valles Marineris
on Mars (B,C)





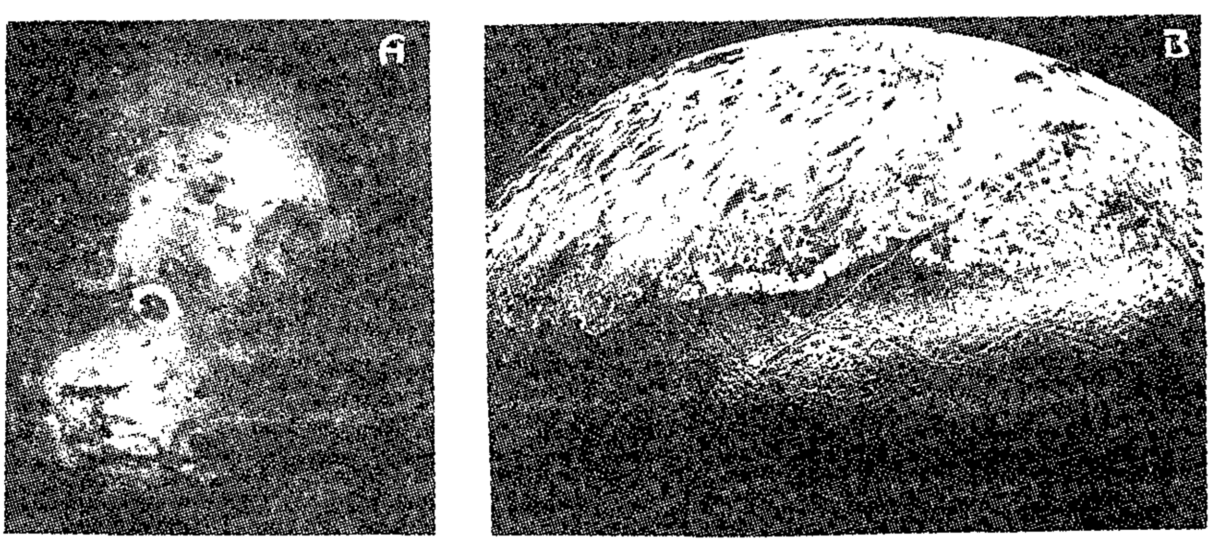
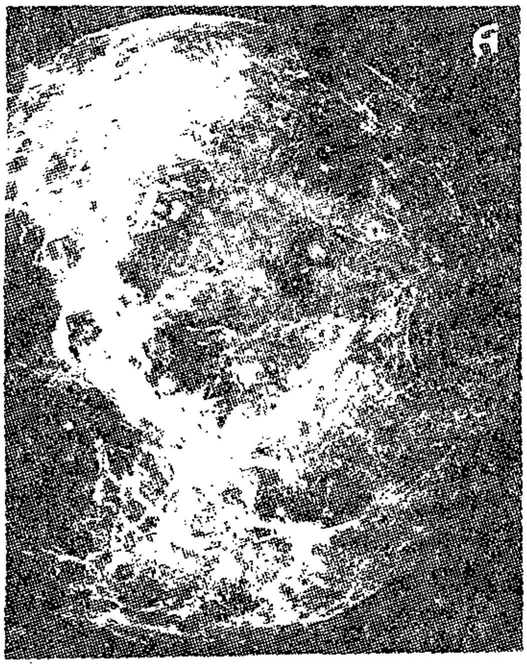


Fig. 3 Io (A), Triton (B)



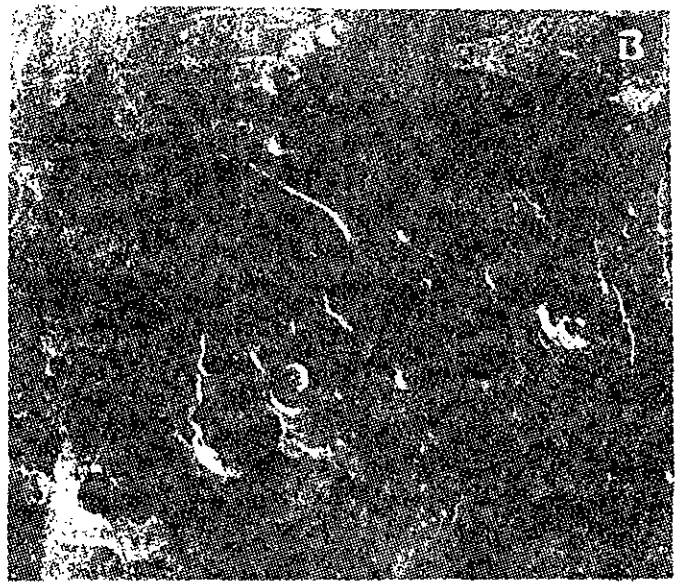


Fig. 4
Venus (A)
Central part of Quetzalpetlatl Corona on Venus (B)
Europa (C)

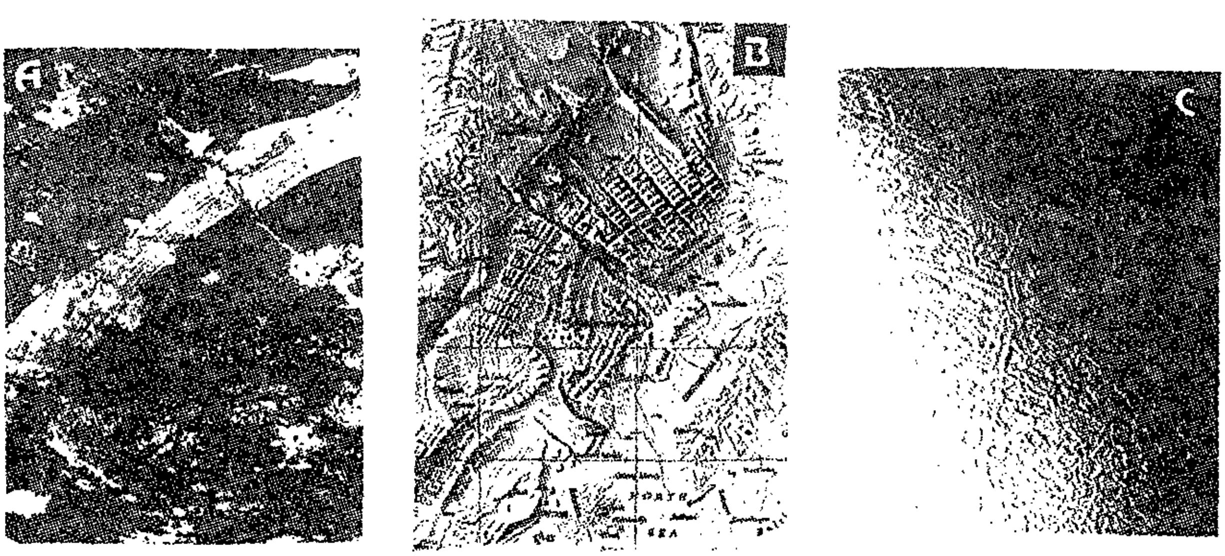


Fig. 5 Transform faults on Ganymede (A), on Earth (B) and perhaps on Triton (C)