INFERRED HEAT TRANSFER MECHANISMS AND TECTONIC DEVELOPMENT OF PLANETS AND SATELLITES

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Abstract. A schematic diagram showing the relative importance of conduction, convection and hotspots as heat transfer mechanisms on planets has been previously described by Solomon and Head (1982). In their construction they *assumed* that the majority of heat transfer on Earth involved mantle convection (and hence, plate recycling), with Io and Mercury dominated by hotspot and conduction, respectively. This diagram is here quantified and used to deduce the tectonic regime of Jovian and Saturnian satellites.

Heat transfer by conduction is a function of the temperature difference, the thickness of the slab through which the heat passes, the slab's area and the material's conductivity. If for a sphere, the thickness is taken as the radius (r), the area as $4\pi r^2$, then for a given temperature difference ($\Delta\theta$) and time (t) the heat transferred by conduction is represented by

$$Q_D = \kappa\, r^2\, 4\pi\, \Delta\theta\, t, \tag{1}$$

whence relative to Mercury (m)

$$(Q_D)_N = \kappa r^2/(\kappa_m {r_m}^2). \tag{2}$$

The thermal conductivity (κ) is expected to be related to density (ρ). Considering the densities and thermal conductivities of ice and olivine, an appropriate relationship between these parameters for a planet/satellite having a density between that of ice and olivine is

$$\kappa = 0.04\, \rho\ [\text{in kg m}^{-3}] - 17, \tag{3}$$

whence the normalised heat transfer by conduction is given by

$$(Q_D)_N = r\, (0.04\rho - 17)/(0.04\rho_m - 17) r_m. \tag{4}$$

For convection the heat transfer equation is

$$Q_V = hA\, \Delta\theta, \tag{5}$$

where h is a convection coefficient and the parameters A, $\Delta\theta$ are as earlier defined. The convective ability of a system is clearly related to its viscosity (η): the more viscous the material the less likely is convection. The assumption is made here that

$$h \propto 1/\log \eta. \tag{6}$$

From estimates of the viscosity of the Earth's mantle of 10^{21} kg m^{-1} s^{-1} (Cathless,

TABLE I

Heat transfer mechanisms for terrestrial planets and Jovian and Saturnian satellites

Planet/Satellite	Transfer mode		
	Conduction[a]	Convection[b]	Hotspot[c]
Mercury	1.0	0.14	0.196
Venus	2.37	0.978	0.857
Earth	2.75	1.00	0.562
Moon	0.42	0.096	0.007
Mars	0.99	0.34	0.025
Io	0.48	0.10	1.00
Europa	0.34	0.083	0.214
Ganymede	0.34	0.29	0.252
Callisto	0.28	0.24	0.059
Mimas	0.016	0.0017	7.62×10^{-4}
Enceladus	0.016	0.0030	8.23×10^{-4}
Tethys	0.037	0.013	0.0052
Dione	0.047	0.014	0.0044
Rhea	0.059	0.027	0.0053
Titan	0.315	0.272	0.0527
Iapetus	0.045	0.025	8.49×10^{-5}

Data for density, radius, and orbital distance from planet for moons given in Stevenson (1986).
[a] Equation (2); normalised to Mercury.
[b] Equation (8); normalised to Earth.
[c] Equation (11); normalised to Io.

1980) and of ice as $10^{12}-10^{13}$ kg m^{-1} s^{-1} (Selby, 1985) an empirical relationship between density and viscosity can be established.

$$\log \eta = 2.83 \times 10^{-3} \rho + 9.68; \tag{7}$$

whence the values for convective heat transfer normalised to Earth may be written as

$$(Q_V)_N = r^2/(0.00283\rho + 9.68)/r_E^2/(0.00283\rho_E + 9.68). \tag{8}$$

The gravitational attraction between two bodies of mass, m_1, m_2, separated by a distance s is given by

$$F_g = Gm_1,\ m_2/s^2, \tag{9}$$

where G is a universal gravitational constant. For bodies within a given system, i.e. rotating about the same body m_1, this can be expressed as

$$Q_T = (Gm_1)\, {}^4\!/_3\, \pi r^3 \rho / s^2. \tag{10}$$

Thus the normalised value of Q_t representing tidal flexing is given by

$$(Q_T)_N = [m_1 r^3 \rho / s^2]/[m_J r^3 \rho_J / s_1^2], \tag{11}$$

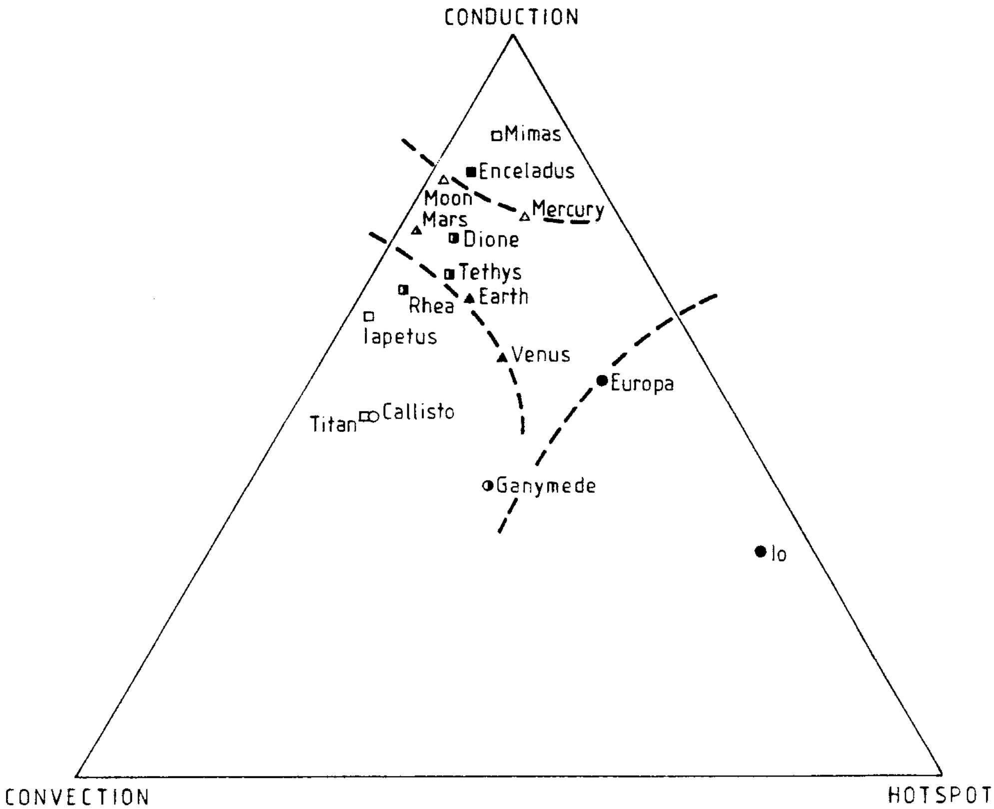

Fig. 1. Relative proportions of conduction, convection, and hotspot heat transfer mechanisms in terrestrial planets, Jovian satellites, and Saturnian satellites.

where the superscript values are those for Io (I) rotating about Jupiter (J). In this equation m_1, is the mass of the Sun for the terrestrial planets, the mass of Jupiter for Jovian satellites, and the mass of Saturn for Saturnian satellites. Thus the data of Table I are obtained. The relative proportions are plotted as a triangular diagram in Figure 1.

The filled symbols on Figure 1 are those planets and satellites that Stevenson (1987) infers to have undergone resurfacing – i.e., evidence of cratering has been removed; whereas open circles indicate that such resurfacing has not occurred. For the terrestrial planets, the relative dominance of convection is apparent, although for smaller bodies (e.g., Mars, Moon, and Mercury) there is an increasing dominance of conduction. For the Jovian system Io by definition shows a clear dominance of hotspots; Europa and Ganymede a convective and hotspot system. Callisto would be expected, on this analysis, to show rather more evidence of crystal recycling than is the case. For the Saturnian system Mimas is inferred to have lost heat only by conduction, whereas Dione, Tethys and Rhea have a comparable tectonic regime to Earth; thus, evidence of tectonism is expected – and found. As for Callisto, the

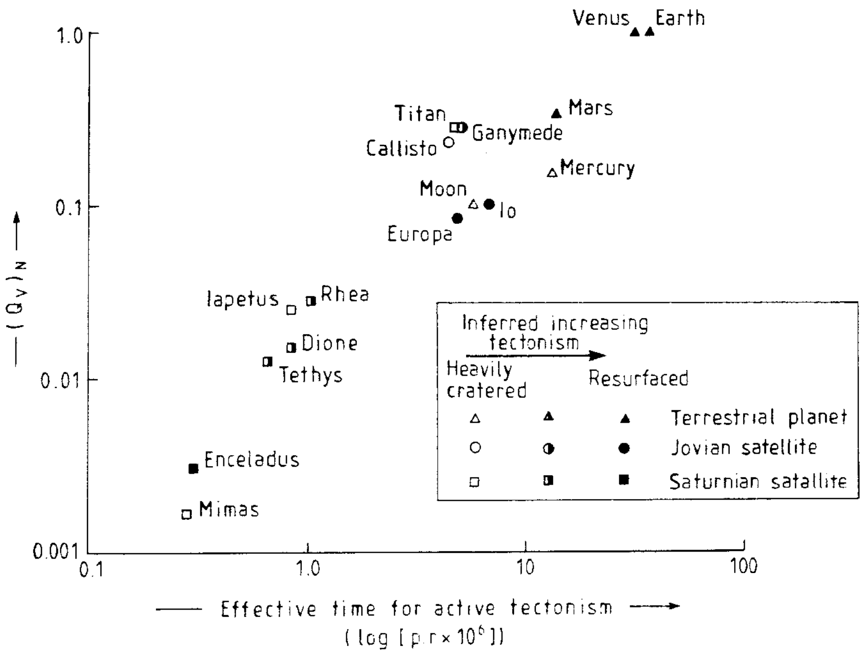

Fig. 2. Intensity of convection driven tectonism normalised to Earth versus the effective time for active internally derived tectonism as the mass to surface area ratio (ρ, r)

absence of tectonism on Iapetus and Titan is not expected on the basis of this analysis. The satellite Enceladus is particularly interesting since, being conductions dominated, no tectonism is expected. Tectonism could be explained by 3-body resonance between other nearby moons, but not including Saturn.

Tidal flexing, giving a hotspot dominant regime, is effectively driven by forces external to the planet or moon. Convective processes, however, may be initiated externally by impact, or more generally as a consequence of decay of radioactive nuclides. Heat loss is enhanced by a greater surface area to mass ratio. Thus the product of density and radius is a proxy for the time available before the heat content of the planet is lost, assuming that the density reflects the concentration of radionuclides.

Figure 2 shows a plot of the intensity of convection driven tectonism $(Q_V)_N$ versus the relative time for active tectonism originating from internal processes alone. It is apparent that the small size of the Jovian and Saturnian moons gives little time for crustal resurfacing, even if the intensity is adequate, before the heat is lost. Thus, some of the impact cratering seen on Tethys, Dione, and Rhea is expected to be post-tectonic and may well be younger populations than those on Mimas. Again, the resurfacing of Enceladus is not expected on the basis of this diagram. The diagram suggests that in the absence of the tidal flexing regime, the Jovian satellites would have been expected to show a comparable tectonic development to the Moon and Mercury.

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