sadly our sampling from those protists most likely to contain these is limited. Other characteristics distinguishing Parabasalia as the earliest eukaryotic lineage are waiting to be discovered — confirmation of the ancient origin of Parabasalia may depend on these characteristics being common in parabasalian genomes.

Patrick J. Keeling*†, Jeffrey D. Palmer*

**Department of Biology, Indiana University, Bloomington, Indiana 47405, USA*

†Present address: Canadian Institute for Advanced Research, Department of Botany, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada

e-mail: pkeeling@interchange.ubc.ca

1. Embley, T. M. & Hirt, R. P. *Curr. Opin. Genet. Dev.* **8,** 624–629 (1998).
2. Philippe, H. & Laurent, J. *Curr. Opin. Genet. Dev.* **8,** 616–623 (1998).
3. Keeling, P. J. *BioEssays* **20,** 87–95 (1998).
4. Stiller, J. W. & Hall, B. D. *Mol. Biol. Evol.* **16,** 1270–1279 (1999).
5. Roger, A. J. *et al. Mol. Biol. Evol.* **16,** 218–233 (1999).
6. Baldauf, S. L. & Palmer, J. D. *Proc. Natl Acad. Sci. USA* **90,** 11558–11562 (1993).
7. Müller, M. *Parasitol. Today* **13,** 166–167 (1997).
8. Embley, T. M., Horner, D. A. & Hirt, R. P. *Trends Ecol. Evol.* **12,** 437–441 (1997).
9. Martin, W. & Müller, M. *Nature* **392,** 37–41 (1998).
10. Liston, D. R. & Johnson, P. J. *Mol. Cell. Biol.* **19,** 2380–2388 (1999).
11. Fast, N. M. & Doolittle, W. F. *Mol. Biochem. Parasitol.* **99,** 275–278 (1999).

Planetary science

Tectonics and water on Europa

The tectonics of Europa, one of Jupiter's moons, are complex. This satellite probably hosts a subsurface water ocean, but the thickness of the outer ice crust is poorly constrained and the episodic presence of liquid water at the surface is debated. We argue that some surface features of Europa are formed by soft ice that is heated by viscous dissipation of tidal motion along faults, and do not depend on a shallow ocean. Our model suggests that transient pockets of liquid water or brine could form at shallow depths in the crust.

The Galileo spacecraft has returned high-resolution images of surface lineations and ridges on Europa. These have prompted proposals that tidal stresses from Jupiter may fracture the icy crust of the synchronously rotating satellite, allowing material from the interior to reach the surface[1,2]. One model invokes tidal expansion and contraction of metre-wide cracks which repeatedly force liquid water up from a subsurface ocean to the surface of the moon as it completes each 85-hour orbit[3] — a process that depends on a thin (1 km or less) ice shell and which has fuelled speculation that the ocean frequently meets the sunlit surface and could be a habitat for life.

The formation of kilometre-deep cracks in Europa's crust is a problem. Below a depth of 35 m, the pressure from the weight of the overlying ice will exceed the estimated stresses due to tides ($<4\times10^4$ Pa) and prevent cracks from growing. Any fractures will halt at a depth where warmer, less viscous ice flows, rather than fracturing further, to accommodate tidal strain. Taking an estimated strain rate of 2×10^{-10} s^{-1} and a relation between normal stress and yield stress appropriate for ice[4], we find that the brittle–ductile transition occurs at depths where temperatures[5] exceed 170 K, well above those of any ice–ocean interface.

Also, liquid water in a crack will freeze solid by virtue of the conduction of heat to the walls: the freezing time is $t = w^2/(16\kappa\lambda^2)$, where w is the crack width, κ is the thermal diffusivity of ice (1.7×10^{-6} m^2 s^{-1}) and λ is a dimensionless parameter[6] equal to about 0.3. A 1-m crack will freeze in 1.3 orbits. Hydrostatic forces are too weak to extrude ice from such a narrow orifice and, unless a compensatory removal of crust occurs elsewhere, the crack will disappear.

We propose, alternatively, that tides drive viscous flow and heating by dissipation at zones of lateral motion (strike–slip) in the crust. There is accumulating evidence for strike–slip motion on Europa[7]. The relative motion along a fault or defect will produce frictional heating, causing the local temperature to increase and the viscosity of the ice to decrease[8]. This feedback can lead to accommodation of the relative motion of two blocks of crust by viscous flow in a zone of finite width, rather than a discontinuity at a fault. Steady-state conditions in the zone are derived by equating the production of heat by viscous dissipation with its loss by conduction to the surrounding ice.

Strike–slip motion of amplitude a at a diurnal period t (3×10^5 s) will maintain a temperature T_c and viscosity η_c at the centre of the shear zone[6] that satisfy $16kRT_c^2t^2 = \pi^2\eta_c E_a a^2$, where E_a and k are the activation energy (6×10^4 J at 273 K) and thermal conductivity (2.1 W m^{-1} K^{-1} at 273 K), respectively, of the ice, and R is the gas constant.

A plausible diurnal motion[3] of 0.6 m can maintain the ice in the centre of the shear zone at a temperature of 273 K, where its viscosity will be roughly 10^{13} Pa s. The width of this zone of soft ice is $\delta = \eta a(\tau t)^{-1}$, where τ is the shear stress (about 1 km for $\tau = 2\times10^4$ Pa). This warm ice will have a buoyant density contrast $\Delta\rho = 20$ kg m^{-3} with respect to the surrounding ice and will flow upwards by a few tens of centimetres over the course of one tidal cycle.

We suggest that such motion over the course of many cycles could be responsible for the formation of structures such as ridge pairs. Our model does require the existence of an ocean (not necessarily shallow): without the mechanical decoupling between the ice crust and the interior, the motion of the crust would be 30–50 times smaller.

Larger strike–slip motion may lead to partial melting (liquid water) in the shear zone. The melt-generation rate scales as $\tau^2(\rho\eta_c L)^{-1}$, where L and ρ are the latent heat of fusion (3.25×10^5 J kg^{-1}) and density (900 kg m^{-3}), respectively, of ice. This production will be balanced by downward percolation of the denser melt at a rate[9] $A\phi^n\Delta\rho g(\eta_m h)^{-1}$, where A and n are constants, ϕ is the melt fraction, η_m is the melt viscosity, h is the thickness of the melt column, and g (1.3 m s^{-2}) is Europa's surface gravity. Although there are considerable uncertainties in some of these values, the equilibrium melt fraction is of the order of 1%. This much melt will form only if the strike–slip motion is sufficiently large ($\sim$1 m) to compensate for the reduction in ice viscosity by a factor of about one third as a result of the presence of melt[10].

The pore pressure due to the presence of melt will also increase the depth to the brittle–ductile transition and allow fractures to accommodate strike–slip motion and to slow heat generation. Melt pockets below the fracture zone will percolate downwards at a velocity of a few tens of metres per year, and so will have a lifetime of $\sim$1,000 years. Any melt at the base of the fracture zone will escape through the fractures or freeze and, if salts are present, brines will be rejected from the freezing melt[11].

In this case, the melt lifetime, estimated by equating the latent heat that must be rejected to the rate of thermal conduction away from the fault zone, will be about 30 years (although shorter at shallow depths, where vertical conduction to the surface is important). Depending on the thickness of the fractured zone, transient liquid-water or brine pockets may exist within reach of sunlight, potentially providing habitats for photosynthetic organisms capable of remaining dormant in ice for millennia[12] between relatively brief 'blooms'.

Eric J. Gaidos*, Francis Nimmo†

**Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA*

†Bullard Laboratories, Department of Earth Sciences, Madingley Rise, Madingley Road, University of Cambridge, Cambridge CB3 0EZ, UK

1. Sullivan, R. *et al. Nature* **391,** 371–373 (1998).
2. Pappalardo, R. T. *et al. J. Geophys. Res.* **104,** 24015–24055 (1999).
3. Greenberg, R. *et al. Icarus* **135,** 64–78 (1998).
4. Rist, M. A. *J. Phys. Chem. B* **101,** 6263–6266 (1997).
5. Pappalardo, R. T. *et al. Nature* **391,** 365–367 (1998).
6. Turcotte, D. L. & Schubert, G. *Geodynamics: Applications of Continuum Physics to Geological Problems* (Wiley, New York, 1982).
7. Tufts, B. R. *et al. Icarus* **141,** 53–64 (1999).
8. Stevenson, D. J. in *Europa Ocean Conf., Capistrano Conf. 5* 69–70 (San Juan Capistrano Res. Inst., CA, 1996).
9. McKenzie, D. *Earth Planet. Sci. Lett.* **74,** 81–91 (1985).
10. Duval, P. *Int. Assoc. Sci. Hydro.* **118,** 29–33 (1977).
11. Cottier, F., Eiken, H. & Wadhams, P. *J. Geophys. Res.* **104,** 15850–15871 (1999).
12. Vorobyova, E. *et al. FEMS Microbiol. Rev.* **20,** 277–290 (1997).