TOFFEE PLANETS: INFLUENCE OF SURFACE GRAVITY ON EXOPLANETARY LITHOSPHERES.

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Introduction: The uppermost, rigid portion of a solid planetary body is termed the lithosphere [e.g., 1]. The lithosphere usually comprises a relatively cold, upper region where brittle deformation occurs, and a relatively warm, lower region that responds to stress in a ductile manner [e.g., 2]. In the brittle lithosphere, tectonic deformation is accomplished by localized fracturing processes, commonly forming shear fractures (i.e., faults). In the ductile regime, deformation is dominantly accommodated by distributed plastic flow mechanisms such as dislocation glide or diffusion creep [e.g., 3]. The region in the lithosphere where brittle behavior gives way to ductile deformation is the brittle–ductile transition (BDT), the depth interval of which is controlled primarily by temperature and strain rate.

The thickness of the brittle lithosphere plays a major role in the geological evolution and behavior of a planetary body, including for example its heat flux [4], style of tectonic deformation [5], and even the evolution of any atmosphere present [6]. Absent in situ geophysical (e.g., seismic and/or heat flux) data, however, there is no direct measure of the depth of the BDT within a planetary body's lithosphere. Instead, this depth can be estimated by forward modeling of the penetration depths of tectonic structures [7], matching models of flexurally induced strains to geological observations [8], and studies of topography–gravity admittance and correlation spectra [9].

Surface Gravitational Acceleration: A wealth of laboratory data show that the failure mode of material is strongly influenced by both temperature and pressure. For example, low lithostatic pressure, *P*, promotes brittle failure in rock [10]. Since *P* is a function of surface gravitational acceleration, *g*, a less massive body but with otherwise similar composition, heat flux, and strain rate will have a deeper BDT, and thus a thicker brittle lithosphere, than a body with greater mass—with concomitant implications for volcanic, tectonic, and thermal properties and evolution [11].

It is therefore possible to place estimates on the BDT depth interval within a differentiated, terrestrial body simply from knowledge of its gravitational acceleration (or, if *g* is not measured directly, its mass), with that depth further affected by some combination of heat flux, atmospheric conditions, and stellar flux. With this technique we have published BDT depth estimates for Venus [6] and Mars [11] (the latter of which will be tested by the InSight mission [12]); here, we extend our approach to considerations of lithospheric structure and behavior for rocky planets in orbit about other stars.

Rock Deformation Data: We compiled published data for rock deformation experiments with basalt and diabase samples, performed at high temperatures and over a wide range of pressures [11]. (These lithologies are appropriate for the majority of the Terran lithosphere, and probably the entire Martian lithosphere [13].) For a body with chondritic relative K–U–Th abundances and an assumed thermal gradient of 25 K/km, this approach yielded a predicted transition from brittle to ductile failure at a depth of ~25 km for Earth [11]—consistent with a BDT interval depth of 10–40 km for oceanic lithosphere calculated with yield strength envelopes [3]. That same thermal gradient predicted a brittle lithospheric thickness for Mars of 30–40 km, with BDT depths of as little as ~25 km and as much as ~100 km for thermal gradients of 40 K/km and 5 K/km, respectively [11]. These findings for Mars are in agreement with the range of estimates for both brittle lithospheric thickness and heat flow derived from inversion of present-day tectonic structures [e.g., 14], and demonstrate the control on failure mode by surface gravitational acceleration alone.

Brittle Lithospheres in Exoplanets: To estimate the depth interval of BDTs in extrasolar planets, we follow a simplified approach that only requires that *g* be known. Assuming a differentiated, chondritic body, we take a rock density, ρ, of 3,000 $kg \cdot m^{-3}$ and, instead of a given thermal gradient, we regard the transition from brittle to ductile failure as occurring at a pressure of 300 MPa (which is the case for basalt at about 300 K [15]). We therefore place the BDT in an exoplanet's lithosphere at a depth, *z*, where the lithostatic pressure is 300 MPa, calculated from $P = \rho \cdot g \cdot z$. Gravitational acceleration, in turn, is found with $g = G \cdot M / r^2$, where G is the gravitational constant ($6.674 \times 10^{-11}\ m^3 \cdot kg^{-1} \cdot s^{-2}$), M is planetary mass, and r is planetary radius.

We consider six exoplanets for which mass estimates are available, and which, on the basis of the relationship between mass and volume, have densities equal to or greater than the terrestrial planets in the Solar System. These selected exoplanets include Kepler-36b [16], Kepler-99b, Kepler-113b, and Kepler-406c [17], and K2-3d [18]. With estimates of mass and radius for these bodies, we first calculate *g* and then determine the

Table 1. *Calculated minimum and maximum depths to brittle–ductile transitions in select extrasolar planets.*

Exoplanet	$M_{\oplus\ min}$[a]	$M_{\oplus\ max}$[a]	$r_{\oplus min}$[b]	$r_{\oplus max}$[b]	g_{min} (m·s^{-2})	g_{max} (m·s^{-2})	z_{min}[c] (km)	z_{max}[d] (km)	Ref.
Kepler-36b	3.7	4.1	1.5	1.5	15.9	18.1	**5.5**	**6.3**	[16]
Kepler-99b	4.9	7.5	1.4	1.6	19.6	37.3	**2.7**	**5.1**	[17]
Kepler-113b	7.5	15.9	1.8	1.9	21.0	49.8	**2.0**	**4.8**	[17]
Kepler-406c	0.9	4.5	0.8	0.9	11.5	65.8	**1.5**	**8.7**	[17]
K2-3d	4.5	10.5	1.3	1.7	14.8	59.1	**1.7**	**3.7**	[18]

[a]$M_\oplus$ is mass of Earth; [b]$r_\oplus$ is radius of Earth; [c]z_{min} is minimum depth within the lithosphere with a thermal gradient of 25 K/km where the overburden pressure is 300 MPa; [d]z_{min} is maximum depth where overburden is 300 MPa.

depths within their lithospheres (assumed to mechanically correspond to basalt) where the overburden pressure is 300 MPa. (We treat g as invariant over the depth ranges we consider here.) To accommodate uncertainties in the measures of planetary mass and radius, we report in **Table 1** BDT depth minima and maxima.

Even though this approach returns a span of BDT depth estimates for each planet, with up to a factor of six difference between minimum and maximum values, it is striking that none of these worlds' predicted BDTs is situated deeper than about 10 km (and several are within 2 km of the surface). Such a depth is comparable to the minimum BDT depth for Terran oceanic lithosphere [3], but substantially less than for continental settings on Earth [e.g., 19] and for the lithospheres of Mercury [7], the Moon [8], or Mars [11].

Other Controls on BDT Depth: Factors additional to g influence the depth interval of the BDT within planetary lithospheres. For example, the relative abundances of heat-producing elements within a body will influence heat flux, with a low thermal gradient leading to a proportionately deeper BDT [e.g., 11]. Therefore, a thermal gradient greater than 25 K/km will yield yet shallower transition depth ranges than those we give in **Table 1**. In the Archaean, the Terran heat flux was up to three times greater than today [20]; a rocky exoplanet that orbits a relatively young star (e.g., the 1.5-Gyr old Kepler-99 [17]) might have a similarly elevated thermal gradient compared with present-day Earth, and thus a proportionately thinner lithosphere. Atmospheric mass and composition, as well as type, age, and distance to the parent star, also influence BDT depth. For example, atmospheric pressure and temperature on the Venus surface is 9 MPa and 735 K, respectively, and stellar irradiance is almost twice that of Earth. Together, these conditions place the Venus BDT, at least in the lowlands, at a depth range of ~2–12 km [6], comparable to those we calculate for our select exoplanets. Particular combinations of planetary mass, atmospheric pressure and composition, and stellar distance and flux are therefore capable of producing a "toffee planet"—one where the lithosphere is thin or even entirely absent, such that the asthenosphere essentially lies at or just below the surface.

The Geology of Toffee Planets: A world with a lithosphere too thin to subduct (or with no lithosphere at all) could not support plate tectonics, with implications for heat loss, style of volcanism, atmospheric composition, and the frequency with which new reactive minerals reach the surface. Bodies with masses sufficient to yield thin lithospheres, then, might host tectonic and volcanic features similar to those that characterize the Venus lowlands [21] or Archean Earth [22], with high-standing terrain the exception, not the rule. This inference can be tested by efforts to search for exoplanet topography [23].

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