LIQUID HYDROCARBONS AND FLUID OVERPRESSURES EXPLAIN CONTRACTIONAL STRUCTURES ON TITAN.

Z.Y.C Liu[1], J. Radebaugh[1], R. Harris[1], and E.H Christiansen[1], [1]Department of Geological Sciences, Brigham Young University, Provo, UT 84602, USA., *zacqoo@byu.edu*.

Introduction: The general observation concerning icy satellite tectonics prior to Cassini was that most satellites exhibit evidence for extensional tectonism, whereas contractional tectonism is rare [1]. However, since Cassini has progressively unveiled Titan's surface beginning in 2004, many studies suggest contractional tectonism may have formed Titan's mountains. Studies have focused on: topography [2-4], morphology [3-7], comparative studies with Earth's tectonic features [7], and structural and stress field analysis [3,8,9]. In particular, models by Mitri et al. [4] suggest volume change due to internal cooling can result in contractional tectonism to form folds on Titan. Thus, Titan may be the only icy satellite on which contraction has occurred in many locations, and in fact may be the predominant style of tectonism.

However, Pappalardo and Davis [10] have argued that in order to form compressional structures on icy satellites, relatively large stresses (>5 times that required to form extensional structures, in the case of Ganymede) are required, and sources of such stresses probably do not exist for most icy satellites. Dombard and McKinnon [11] calculated that fold formation on Europa requires driving stresses of ~9-10 MPa, whereas extension only needs 0.1~1 MPa of stress. Therefore, a paradox has emerged that there is no stress source large enough to explain the contractional structures observed on Titan.

In this study, we provide a solution for this paradox: fluid overpressures associated with liquid hydrocarbons (e.g. methane, ethane) significantly reduce the shear strength of the icy crust of Titan and enable contractional structures to form without the requirement of large stresses. Overpressured subsurface liquid hydrocarbons on Titan can: (1) offset the normal stresses on icy rock surfaces and support the weight of thrust sheets, and (2) decrease friction strength in the detachment fault zone and enable icy rock sheets to slide to form folds. Therefore, if the fluid pressure is high enough to offset the normal stress, the force needed to form thrust faults must only exceed the cohesive strength of icy rock, which is only the order of 0.1 ~1 MPa [12]. Then, only small stresses are needed to overcome sliding friction to form fold-thrust belts.

We discuss liquids on Titan and the strength of ice and then use the Critical Wedge Mechanism [13] to test if crustal conditions on Titan favor the formation of folds and thrusts.

Subsurface liquid hydrocarbons: Titan's atmospheric pressure of 1.5 bars and temperature of 94 K allow hydrocarbons to be stable on the surface as liquids in lakes [14] and river channels [15] which is a unique condition among icy satellites. Recent studies [16,17] strongly suggest that methane liquids also flow below Titan's surface. Moreover, Griffith et al. [18] discovered possible tropical lakes, and concluded that these low latitude lakes on Titan are best explained as supplied by subterranean aquifers. Thus, Titan has a hydrologic cycle that likely includes a ground "methane" system similar to Earth's groundwater system. Because Titan's upper crust is below the liquid methane table [19], the porosity of rocks must be filled with fluid. If the permeability is restricted and the fluid is trapped, the pore pressure may exceed hydrostatic pressure which means the fluid is overpressured.

Analogy of Strength Paradox on Earth: On Earth, many large thrusts require displacements of rock over horizontal distances up to 100 km but the stresses needed to satisfy this requirement exceeds the crushing strength of granite, a condition that spawned the *strength paradox* in the field of structural geology. However, Hubbert and Rubey [20] provided a solution for this paradox. Given sufficiently high fluid pressures, thin fault blocks can be pushed over nearly horizontal surfaces to form large overthrusts. They demonstrated the fundamentals of the fluid pressure model in their now-famous beer can experiment. This solution to the paradox involved modifying the Mohr-Coulomb law of frictional shear strength [20]:

$$\tau = C + \mu(\sigma_N - P_f) \qquad (1)$$

where τ is the failure stress required to cause slip, C is cohesion, μ is the coefficient of internal friction, σ_N is normal stress and P_f is fluid pore pressure. When fluid is unable to escape from a porous, but impermeable subsurface horizon, fluid pressures (P_f) support most of the weight of the overlying rock or ice, which reduces the frictional resistence to sliding of this horizon to near zero. When the fluid pressure is high enough to offset all the normal stress (σ_N), the shear stress (τ) needed to form the thrust fault must only exceed the cohesive strength of rock and then a small push can easily overcome the sliding friction to form overthrust sheets and related folds.

Here we adapt the fluid pore pressure effect for conditions on Titan to explain the formation of thrusts and folds. By adjusting equation (1) for Titan, the cohesive strength of icy clathrate rock with possible impact pre-fractures is ~0.1 to 1 MPa [12]. Therefore to form the contractional structures on Titan a large stress (>10 MPa) is not necessary. Only a stress of ~0.1 to 1 MPa is required to form thrust faults. Even Titan's diurnal tidal stress~ 0.026 MPa, may be able to overcome sliding friction to form folds and thrusts.

Furthermore, because the subsurface liquid hydrocarbon layer in Titan's icy crust is most likely located above a depth of 15 km [19], thrust and crustal deformation do not involve the entire thickness of the icy crust. This type of deformation is called "*thin-skinned*" tectonics. Since thin-skinned structures are usually wedge shaped [21], we then evaluate Titan's crustal parameters and slopes of mountains to test if the thrust-folds can form in a critical wedge setting.

Critical Wedge Mechanism: The critical wedge mechanism [13] is a well-established process for driving fold-and-thrust belt formation on Earth, such as the Himalaya foothills and the mountain belts of western Taiwan. The wedge model requires high fluid pressure [20] in the subsurface to weaken the deforming rocks; without high fluid pressures, folds and thrusts would not form. Nahm and Schultz [22] applied critical wedge to explain the formation of Thaumasia Highlands on Mars; however, the wedge model was unable to explain the mountains belts on Mars because there is little subsurface water.

A critical wedge model can be described using equations that characterize the physical properties and geometry of the wedge (Figure 1). The surface slope α of a mechanically homogeneous wedge is related to the dip angle of the decollement β. Equations are modified from Suppe [23]:

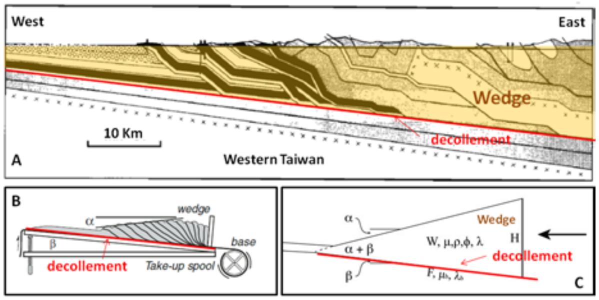
$$\beta = (\mathbf{F} - \alpha[(1 - (\rho f/\rho)) + \mathbf{W}])/\mathbf{W} \tag{2}$$

$$\mathrm{F} = \mu b(1-\lambda) + Sb/\rho gH \tag{3}$$

$$W = 2(1-\lambda)[sin\phi/(1-sin\phi)] + C/\rho gH \tag{4}$$

The explanation of the parameters in equations (2)-(4) and basic physical/mechanical properties of Titan are listed in Table 1. The application of the critical wedge model to Titan is tested by comparing measured slope angles of the fold and thrust belts across Titan to the values required by thrusting in a critical taper wedge setting [22]. The topographic data and slope of mountains on Titan are generated by the SARTopo technique [24]. Fluid pore pressure ratio (λ) is defined by the density of icy crust and fluid: $\lambda = P_f / \rho gz$. On Titan, λ is 0.67 and here we consider an overpressured fluid. Thus, we use $\lambda = 0.7$ to 1 in our calculation. The calculated decollement base (1.5-2 km) is above the liquid methane table which decreases the shear strength in decollement. In calculation, we assume the coefficient of friction in wedge is larger than that in decollement ($\mu > \mu_b$).

Results: Thus far, we have evaluated 10 regions of possible fold-and-thrust belts in a critical wedge settings on Titan. The average slopes of 10 mountain are all below 1.5^o. In our calculation, we input the measured slope α with varying μ_b (0.3-0.8), μ (0.3-0.8) [26] and λ (0.7-1) to calculate the range of dip angle β values (equation 2). On Earth, $0^o \leq \beta \leq 10^o$ is considered to be a reasonable range [12,22]; thus, we adopt this for our calculations. Of the 560 cases for 10 mountain belts, 400 cases (71%) of β values were found where $0^o \leq \beta \leq 10^o$. Thus, our results indicate that these 10 mountain belts were very likely formed in a critical wedge setting. The calculation results for the 200^{o}W mountain belt are shown in Figure 2. The graphs show the calculated decollement dip angle β versus the wedge friction coefficient μ with the friction coefficient of the decollement varying μ_b.



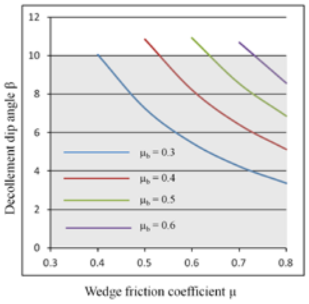


Figure 1. (Top) Schematic geometry of a critical taper orogenic wedge. Modified from [13,22,23]

Figure 2. (Left) Shaded areas show the calculated dip angle β range in reasonable values which indicate the critical wedge is very likely to form on Titan.

Dussions and Conclusions: The high pore fluid pressure estimated for Titan predicts that under contractional stress conditions a critical wedge should form. Furthermore, the critical wedge model is applicable for Titan because: (1) the pore fluid pressure ratio without overpressures on Titan is $\lambda = 0.67$, while on Earth $\lambda = 0.37$, which indicates that the environment on Titan is more favorable for the formation of a critical wedge than Earth. (2) On Titan, the reaction of fluids (methane) with potential surface materials (clathrates or organics) makes the near-surface crust weaker and easier to break [24] to form thrusts and folds than a pure water ice crust. (3) The calculated decollement depths (1.5-2 km) lie within the cohesive boundary (2-5 km), thus the brittle-ductile transition boundary (2-3 km) [25] is favorable for formation of the critical wedge on Titan.

In summary, hydrocarbon liquids on Titan facilitate the formation of fold-and-thrust belts without large stresses. This has played a key role in Titan's tectonic evolutionary history. We expect the results will lead to a reevaluation of the geological significance of fluids in planetary lithospheres; a process that appears to be unique to Earth and Titan in our solar system.

References: [1] Collins, G.C. et al. (2009) *Planetary Tectonics, Chapter7*, p. 264–350. [2] Radebaugh, J. et al. (2007) *Icarus 192,* 77-91. [3] Liu, Z.Y.C. et al. (2012) *LPS 43rd Abstract* #2378. [4] Mitri G. et al. (2010) *JGR 115,* E10002. [5] Radebaugh, J. et al. (2011) *Icarus 211*, 672-685. [6] Wood, C. et al. (2012) LPS *43rd Abstract* #1628. [7]Solomonidou, A. et al. (2012) *Planetary and Space Science*, In Press. [8] Cook, C. et al. (2012) k*LPS 43rd Abstract* #2484. [9] Paganelli, F. et al. (2010) *LPS 41stAbstract* #2664. [10] Pappalardo, R.T. and Davis, D.M. (2007) *Workshop on Ices, Oceans, and Fire, vol 1357*, pp. 108-109. [11] Dombard, A.J. and McKinnon, W.B. (2006) *J. of Structural Geology 28*, 2259-2269. [12] Beeman, M. et al. (1988) *JGR 93*, 7625-7633. [13] Davis, D.M. et al. (1983) *JGR 88, no. Nb2*, p. 1153-1172. [14] Stofan, E.R. et al. (2007) *Nature, v. 445*, no. 7123, p. 61-64. [15]Lorenz, R.D. et al. (2008*) GRL 35*, 02206. [16] Hayes, A. et al. (2008) *GRL v. 35*, no. 9. [17] Tomasko, M.G. et al. (2005) *Nature, v. 438*, 765-778. [18] Griffith, C.A. et al. (2012) *Nature, v. 486*, 237-239. [19] Vance, S. et al. (2012) LPS *43rd Abstract* #2939. [20] Hubbert, M.K. and Rubey, W.W. (1959) *Bulletin of the Geological Society of America*, v. 70, pp. 115-166. [21] Chapple, W.M. (1978) *Geological Society of America*, v. 89, pp. 1189-1198. [22] Nahm, A. L., and Schultz, R. A. (2010), *JGR 115*, E04008. [23] Suppe, J. (2007) *Geology, v. 35*, no. 12, p. 1127-1130. [24] Stiles, B.W. et al. (2009) *Icarus, v. 202*, no. 2, p. 584-598. [25] Li, Y. et al. (2012) *Energies, 5*, 181-192. [26] Nimmo, F. and R. T. Pappalardo (2004) *GRL, 31*, L19701. [27] Schulson, E.M. et al. (2012) *JGR 117*, No. B12, B12204. [28] Schenk, P.M. (1991) *JGR 96*. [29] Iess, L. et al. (2010) *Science, 327*, 1367-1369. [30] Lorenz, R.D. (2002*) Icarus 156*.

Table 1

Parameters	Description	Values and sources
μ	Wedge friction coefficient	0.3, 0.4, 0.5, 0.6 [27]
Φ	Angle of internal friction for the wedge	16.7^o, 21.8^o, 26.6^o, 31^o ($\Phi = \tan^{-1}\mu$)
ρ	Density of the wedge material	900 kg m^{-3} (water ice) [28]
λ	Pore fluid pressure ratio	0.7-1
α	Surface slope	Measured
C	Wedge cohesion	1 MPa [12]
W	Wedge strength	Calculated
H	Wedge thickness	Measured
S_b	Decollement cohesion	1 MPa [12]
μ_b	Decollement coefficient of friction	0.3-0.8 in 0.1 increments
F	Decollement strength	Calculated
β	Dip angle of decollement	Calculated
g	Acceleration due to gravity	1.352 m s^{-2} [29]
ρ_f	Density of the overlying fluid	600 kg m^{-3} [30]