

A Hypothesis: A Condition of Growth of Thick Ice Wedges

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So-called Ice Complex or “edoma” in Siberia, which represents extremely ice-rich and perennially-frozen sediments with thick polygonal ice wedges, is formed in territories acting as terrestrial accumulation basins during the Pleistocene. It sometimes consists of more than 90% ice by volume. Simplifying, a decrease of temperature causes soil to shrink and cracks to form; then water seeps into the cracks in spring. It freezes and expands when it is chilled by permafrost. This cycle continues to enlarge the wedges year by year until the soil above the wedges is pushed up and finally almost disappears around. However, details of the mechanism of thermal contraction cracking and ice wedge formation still remain unclear (French 1996). Ice is known to be able to flow under loads, and it probably could be easier for ice to be pressed up than for soil. Why do we observe the result of soil pushing up only, not ice, and what is the mechanical condition of the process?

Water freezing and expanding when it is chilled by permafrost can be expressed by the Clapeyron equation. Stresses can be estimated approximately as 13.4 MPa per a decrease in negative temperature by 1°C. In the case of mechanical equilibrium, if horizontal stresses σ_z are equal in soil and ice, the heaving strain of about 9% of volume of freezing water ε_f is connected to mechanical compression of frozen soil ($d\sigma_z * l_f / E_f$) and ice ($d\sigma_z * l_{ice} / E_{ice}$), being of l_f and l_{ice} in size and having the strain modulus E_f and E_{ice} respectively:

$$d\sigma_z = \frac{d\varepsilon_f}{\frac{l_f}{E_f} + \frac{l_{ice}}{E_{ice}}} \quad (1)$$

If, for example, ε_f is 0.0045 m as a result of freezing of 0.05 m of water, $l_f = 5$ m and $l_{ice} = 0.5$ m, and the long-temp compression modulus $E_f = 20$ MPa and $E_{ice} = 50$ MPa, then stress $\sigma_z = 0.017$ MPa. In many cases, the value of ε_f is even less than 0.05 m; for example 0.001–0.003 m only in Barrow (Black 1951), and 0.002–0.01 m in Kolyma plain (Berman 1965). Due to higher modulus values, compression of soil reaches 4.33 and ice 0.17 mm consequently. The size of the deformed soil area varies, for example, near Fairbanks in the range of 0.3–3 m (Pewe 1962). The lateral strains depending on Poisson’s ratio will be less than compression, but probably they will be more for soil than for ice. Stresses are small and perhaps unable to make considerable structural changes of soil mass. Repeating a thousand times, it results in ice wedge thickness of about 4 m. This is generally in agreement with the point that soil is pushed up during ice wedge formation. However, it was found that soil layers at a certain distance from the ice wedge are almost not affected (Popov 1965).

An area of high density of deformed soil should be created on contact with an ice wedge to give space to ice, and that

area should be gradually increased in size in accordance with an increase of wedge thickness. One reason for the deformed area to remain small is the stress distribution in soil mass. The stresses are basically not equal and become smaller with distance from an ice wedge. Using q /unit length on the surface of a semi infinite soil mass, or if the excess stress is according to the Boussinesq equation (Ahlvén & Smoots 1988), the stress can be found approximately:

$$\Delta\sigma_z \sim \frac{\sigma_z}{z^n} I \quad (2)$$

where n changes from about 1 to 2, I = influence factor for the load, and z = distance from the ice wedge. Formula (1) should be adjusted then according (2). If horizontal stress $\sigma_z = 0.017$ MPa near an ice wedge, it is about $\sigma_z = 0.004$ MPa only on distance of 2 m. Thus, stresses might be too small to cause deformations far from the ice wedge, but they are big enough to move soil particles and pore ice near the ice wedge. Another reason for the deformed area to be small is perhaps because of gradual movement of attached ice soil towards the surface together with ice caused by pressure and buoyancy.

Signs of diapirism and soil circulation are widespread in periglacial areas (Hallet & Waddington 1991). Buoyancy can be an effective driving force in the case of ice wedges due to different densities of frozen soil (1.5–1.7 and more cm^3/g) and ice (0.9–1 cm^3/g). If the size of polygons are more than or equal to the height of an ice wedge h , and the viscosity of ice η_i is much less than the viscosity of the surrounding soil η_s , the rate of vertical movement of an ice wedge wall v will be (Artyushkov 1969):

$$v \sim \frac{\Delta\rho g h^2}{\eta_s} \quad (3)$$

where $\Delta\rho$ = difference of densities of soil and ice; g = gravity acceleration, 9.81 m/sec; η_s = viscosity of surrounding soil, Pa*s. However, the assumption that the viscosity of ice is less than the viscosity of the surrounding soil is far from being acceptable: relationship is opposite. The ice viscosity can be assumed as 10^{12} – 10^{13} Pa*s, and frozen soil viscosity as 10^{10} – 10^{11} Pa*s. The buoyancy of an ice wedge and its vertical movement z can still be found from the similar Navier-Stokes equation:

$$z \sim vt \sim \frac{\Delta\rho g l^2}{18\eta_s} t \quad (4)$$

where t = time; l = width of ice wedge. If the width of the ice wedge $l = 1$ m, and time t is 1000 years, then resurfacing of ice can reach about 1.5 m. That value of vertical movement may change the shape of ice wedges drastically, especially in saline or high-temperature permafrost. Vertical orientation of

rod-shaped air bubbles (Kurdyakov 1965), "echelon breaks" (Pewe 1962), and the foliated structure of ice can serve as indirect evidence of it. Sometimes soil layers near an ice wedge look like they are "drawing in ice" (Pewe 1962). Flexures of soil layers near ice wedges are mostly directed up (Popov 1965) probably because of vertical ice flow. Unusual deformations of soil layers under an ice wedge, described by Kostyaev (1965) in the Yana River terrace, can also be a result of buoyancy. Ice wedges flowing upward 1–3 m, like diapers, were described by Black (1983).

Therefore, the thick ice wedges can be formed easier in conditions of low values of the soil creep threshold σ_0 and their higher deformability; it is a condition of their growth by the cracking-fullfilling-freezing mechanism. Stresses induced by freezing are small and perhaps unable to make considerable structural changes of soil mass. However, creep threshold σ_0 values of frozen saline soil are low, and that gives a vital reason for wide distribution of thick ice wedges in regions of saline permafrost. Ice is able to flow at any stress, and should be flowing up during ice wedge formation. A number of features appears to be created during the evolution of ice wedge shape due to the flow; among them irregular shapes of underground ice are common. Buoyancy can be another effective driving force in the case of ice wedges due to the difference of densities of frozen soil and ice. An estimation shows the buoyancy of ice can reach substantial values.

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