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Autor: Hsü, K. Jinghwa

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A preliminary Analysis of the Statics and Kinetics of the Glarus Overthrust

by K. JINGHWA HSÜ

Geological Institute, Swiss Federal Institute of Technology, Zürich

ABSTRACT

The theoretical treatment on the statics of overthrust faulting by HUBBERT and RUBEY did not take account of the role of initial shearing strength of rocks (in case of failure by flowage), or the initial shearing resistance of fracture surfaces (in case of frictional sliding). This apparently minor omission led to grossly misleading tectonic analyses.

Based upon observations of the nature of deformation along the Glarus thrust plane, I concluded that the main movement of the thrust was related to a zone of flowage at its base, the Lochseitenkalk. Later the thrust slid along a pre-existing fracture plane within the Lochseitenkalk, producing a thin film of fault gouge through the elimination of minor irregularities on such fracture surfaces.

A consideration of the statics gives two equations relating five variables, the length x_1, and the thickness z_1 of the thrust plate, the angle of the thrust plane θ, the pore pressure – overburden pressure ratio λ_1, and the critical angle θ_c necessary for gravity-sliding. The first three variables on thrust geometry could be estimated by geologists, thus permitting an estimate of pressure conditions and of the possibility of gravity sliding. Tentative conclusions are

(1) The main Glarus movement, along a nearly horizontal thrust plane, was caused by a push from behind, when the pore pressure at the base of the thrust was almost equal to the overburden pressure.

(2) The later movement, down a 10° slope, may have been gravity-sliding, if the pore pressure remained abnormally high, otherwise additional push from behind would be necessary.

A consideration of the kinetics gives six equations relating the dimensions of a thrust block to six variables, rate of overthrusting dx/dt, stress τ, equivalent viscosity η', strain rate $\dot{\varepsilon}$, temperature T, rate of mechanical generation of heat Q_b. Accepting the geometrical dimensions of the thrust given by field geologists, the main Glarus overthrust was estimated to have moved at a rate not slower than 0.2 cm/yr and not faster than 10 cm/yr, while the temperature at its base was not lower than 300 °C and not higher than 400 °C.

The later phase of Glarus overthrust was characterized by jerky movements of frictional sliding, whereby sudden, but small thrust displacements repeatedly relieved the stress build-ups. The average rate of the accumulative displacement was governed either by the rate of eroding the obstruction in front of the thrust (in case of gravitational sliding), or by the advance rate of the nappe at its rear (in case of push from behind).

ZUSAMMENFASSUNG

Die theoretische Behandlung der Überschiebungsmechanik von HUBBERT und RUBEY hat den Effekt der Kohäsion (im Falle von Verformungen durch Fliessen) oder des anfänglichen Schubwiderstandes einer Bruchfläche (im Falle von Bewegungen durch Reibungsgleitung) vernachlässigt. Diese scheinbar harmlose Weglassung eines kleinen Gliedes in der Gleichung des Spannungsausgleiches führte zu falschen tektonischen Auffassungen.

Aus den Beobachtungen an der Basis der Glarner Überschiebung kann geschlossen werden, dass die Hauptbewegung der Überschiebung durch das Fliessen des Lochseitenkalks ermöglicht wurde. Später glitt die Überschiebungsmasse über eine Bruchfläche; durch kleinere Unregelmässigkeiten an dieser Bruchfläche entstand das pulverisierte Gesteinsmehl zwischen dem Lochseitenkalk.

Eine Berücksichtigung des Spannungsausgleiches ergibt zwei Gleichungen mit fünf Variablen: Länge x_1 und Dicke z_1 der Überschiebungsmasse, die Neigung der Überschiebungsfläche θ, das Verhältnis Porendruck – Überlastungsdruck λ_1, und der kritische Winkel für Schweregleitung θ_c. Da die Geometrie der Glarner Überschiebung – und damit die ersten drei Variablen – durch die Untersuchungen der alpinen Geologen bestimmt worden ist, konnte der Druckzustand und die Möglichkeit der Schwerkraftgleitung geschätzt werden. Meine vorläufigen Schlussfolgerungen sind:

1. Während der ersten Hauptphase wurde die Glarnerüberschiebung auf einer subhorizontalen Überschiebungsfläche durch einen Stoss von hinten in Bewegung gesetzt, als der Porendruck ungefähr gleich dem Überlastungsdruck war.

2. Die spätere Bewegung, die mit einem Gefälle von 10° erfolgte, kann durch die Wirkung der Schwerkraft entstanden sein, falls der Porendruck abnormal hoch blieb; andernfalls musste die Überschiebungsmasse immer noch von hinten gestossen werden.

Eine Berücksichtigung der Kinetik ergibt sechs Gleichungen, die die Dimensionen der Überschiebungsmasse (x_1, z_1) und die sechs Unbekannten – Schubgeschwindigkeit dx/dt, Schubspannung τ, scheinbare Zähigkeit η', Dehnungsgeschwindigkeit $\dot{\varepsilon}$, Temperatur T, Wärmeerzeugung durch mechanische Arbeit Q_p – in Verbindung bringen. Aus den Lösungen der Gleichungen schloss ich, dass sich die Glarner Schubmasse während der Hauptphase der Überschiebung nicht langsamer als 0,2 cm/Jahr und nicht schneller als 10 cm/Jahr bewegte, falls die Temperatur an ihrer Basis nicht niedriger als 300 °C und nicht höher als 400 °C war.

Später glitt die Glarnermasse durch ruckartige Bewegungen weiter ab, wobei plötzliche aber kleine Verschiebungen die Schubspannung periodisch kompensierten. Die durchschnittliche Überschiebungsgeschwindigkeit war abhängig von der Erosionsgeschwindigkeit des Hindernisses vor der Glarnermasse (im Falle von Schweregleitung) oder von der Vormarschgeschwindigkeit der anstossenden Decke (im Falle eines Stosses von hinten).

Introduction

Earlier treatises on the mechanics of overthrusts considered only the friction at their base in order to estimate the minimum resistance (Smoluchowski, 1909). The friction factor alone apparently would restrict the maximum length of an overthrust to 8 km. Facing such a paradox. Oldham (1921) suggested that large overthrusts moved like the crawl of a caterpillar, which advances one part of its body at a time, and all parts in succession. The brilliant effort by Hubbert and Rubey (1959) to solve the mechanical paradox of overthrusts, wittingly or unwittingly, included both of those assumptions: The expression caterpillar crawl was substituted by the modern terminology «dislocation» mechanism, which purportedly eliminated the cohesive strength in succession, so that the resistance to overthrusting was friction only. This faulty analysis led Hubbert and Rubey to underestimate greatly the shearing resistance at the base of overthrusts, and greatly overestimate their length, and the ease of gravitational sliding along very gentle slopes.

I have shown that the Hubbert and Rubey analysis is not applicable to those overthrusts whose movement was related to the flowage of ductile materials within the thrust zone, and have proposed a new treatment of the mechanics of such thrusts (Hsü, in press). A modification of the proposed solution can be extended to account for the overthrusting along pre-existing fracture surfaces.

The mechanics of the Glarus overthrust will be analysed as an illustration of the principles involved. I am indebted to my colleague, Rudolf Trümpy, who enlightened

me on the kinematics of the thrust; to my esteemed friend, King Hubbert, who called my attention to some recent work on stick-slip; and to my assistant, Christoph Siegenthaler, who programmed the computations.

Criterion of shear failure and stress equilibrium

The MOHR-COULOMB equation defines the critical stress τ_c necessary to cause the brittle fracture of materials:

$$\tau_c = \tau_0 + \sigma_n \tan\phi_i \tag{1}$$

where σ_n is the effective normal stress across the potential fracture plane, and $\tan\phi_i$ the coefficient of internal friction. The second term on the right side of equation (1) expresses, therefore, the frictional resistance to fracturing. The first term, τ_0, is an experimental constant, and has been named variously as 'initial shear strength' (HUBBERT and RUBEY, 1959, p. 124), or as 'cohesive strength' (HANDIN, et al., 1963).

Surprising is the experimental fact that the criterion for the ultimate strength of materials undergoing ductile deformation, under pressures of a few kilobars and temperatures of a few hundred degrees, takes the same form as equation (1) (HANDIN, et al., 1963; HSÜ, in press). An even more surprising fact is the discovery by BYERLEE (1967) that the critical stress necessary to induce frictional sliding along preexisting brittle fracture surfaces can also be defined by a relation similar to equation (1).

$$\tau_c = \tau_0' + \sigma_n \tan\phi_s \tag{2}$$

where ϕ_s is the coefficient of sliding friction, and τ_0' is another experimental constant, representing the ordinate of the Mohr envelope for the critical shear stress of sliding when σ_n equals to zero (HSÜ, in press). I proposed to call the term τ_0' 'initial shearing resistance' to frictional sliding.

These relations indicate that the shearing resistance to overthrust faulting includes two terms:

(1) a constant term, the so-called cohesive strength, or initial shearing resistance, and

(2) a variable frictional term, which is directly proportional to effective normal stress.

HUBBERT and RUBEY (1959) erred when they considered only the second term in their equation of stress equilibrium. I have remedied this mistake and derived the following equations (HSÜ, in press; 1968):

$$x_1 = \frac{1}{[\tau_0 + (1-\lambda_1)\tan\phi_i\,\varrho_b\,g\,z_1\cos\theta - \varrho_b\,g\,z_1\sin\theta]}\left[a\,z_1 + \frac{b\,(1-b)\,\lambda_1}{2}\,\varrho_b\,g\,z_1^2\cos\theta\right] \tag{3}$$

$$\theta_c = \cos^{-1}\frac{-m\,n + \sqrt{(m\,n)^2 + (1-m^2)(1+n^2)}}{(1+n^2)} \tag{4}$$

when

$$m = \frac{\tau_0}{\varrho_b\,g\,z_1} \qquad n = (1-\lambda_1)\tan\phi_i$$

The expressions τ_0 and $\tan\phi_i$ in these equations should be replaced by τ_0' and $\tan\phi_s$, if the overthrust did not flow, but slid along a pre-existing fracture surface.

The factors involved in these two equations are as follows:

(1) An experimental constant of accurately known value, namely gravitational acceleration $g = 980$ cm/s^2.

(2) Experimental constants of limited applicability, which are ϕ_i (or ϕ_s), ϱ_b, $\boldsymbol{a}$, $\boldsymbol{b}$, τ_0 (or τ_0'), where

ϕ_i is the angle of internal friction and is on the average 30° so that the average $\tan\phi_i$ is 0.577, about the same as that of sliding friction ($\tan\phi_s$), although the value may range from 0.4 to 1.0 (HANDIN and STEARNS, 1964).

ϱ_b is the density of water-saturated sedimentary rocks. A value of 2.3 g/cm^3 has been assumed in computations by HUBBERT and RUBEY (1959), by LAUBSCHER (1961), and by myself (HSÜ, in press), although the value for the rocks of the Glarus overthrust may have been somewhat larger.

$\boldsymbol{a}$ and $\boldsymbol{b}$ are constants relating the maximum and minimum principal stresses σ_1, and σ_3 at shear failure by the relation

$$\sigma_1 = a + b\,\sigma_3\,. \tag{5}$$

Since $\boldsymbol{a} = \sigma_1$, when σ_3 is zero, we could consider $\boldsymbol{a}$ the compressive strength of a material under atmospheric conditions. An average value $\boldsymbol{a} = 7 \times 10^8$ dynes/cm^2 for sedimentary rocks has been determined by experiments.

The constant $\boldsymbol{b}$ is related to friction angle ϕ_i by the relation

$$b = \frac{1 + \sin\phi_i}{1 - \sin\phi_i} \tag{6}$$

and is, therefore, 3 for $\phi_i = 30°$.

τ_0 is the initial shear strength. The average value for sedimentary rocks of 2×10^8 dynes/cm^2 is determined by experiments (HUBBERT and RUBEY, 1959, p. 126; HANDIN et al., 1963, p. 736).

The value of τ_0' has not yet been thoroughly investigated. BYERLEE's work (1967) showed that the τ_0' value of sliding along water-saturated pre-cut surfaces of granite specimens is 10^8 dynes/cm^2. However, experiments by HEARD and RUBEY (1966) could be interpreted to indicate that τ_0' is 3×10^7 dynes/cm^2 for the deformation of dehydrated gypsum, which lost cohesion during phase changes (HSÜ, in press).

(3) Variables in the equations, which are x_1, z_1, λ_1, θ, θ_c, where

x_1 is the length of the overthrust block, z_1 its thickness and λ_1 the pore pressure to overburden pressure ratio at its base.

θ is the dip of overthrust plane, and θ_c the critical angle of gravitational sliding.

The equations (3) and (4) can thus be considered two basic relations in the statics of overthrust faulting: the former relates the dimensions of the overthrust blocks to the dip of the thrust plane and to pressure conditions; the latter gives the minimum critical angle θ_c needed for an overthrust block to slide under its own weight. Both of these equations include more than one variables; their solution depends upon field evidence which may permit certain assumptions on the values of some variables.

The statics of the Glarus overthrust

Of the four variables in equation (3) the length of the Glarus overthrust could be estimated with some assurance, ranging from some 30 to 35 km. The thickness of the thrust plane must have been greater than the 3 km under the Glärnisch; R. TRÜMPY suggested that the thrust may have been 5 to 6 km thick at the time of deformation.

The thrust plane is now an arched surface. An estimate of its initial dip depends upon a geological reconstruction. An examination of the thrust contact suggests that it must have undergone two phases of deformation. Figure 1 is a sketch made by ALBERT HEIM (1929) of the thrust contact at Lochseite locality, Glarus. Between the upper and lower plates is the famous Lochseitenkalk, less than 1 m thick, which shows clear sign of flowage. This smeared-out limestone is present practically everywhere under the Glarus thrust. I have taken this as an evidence that the upper thrust plate moved forward as the Lochseitenkalk flowed (HSÜ, in press). In addition, a fault gouge zone, or a clay film, a few millimeters thick, is present as a planar septum within the limestone. Fault gouge has been produced experimentally when one block slid past another along a pre-existing fracture surface, as noted by BYERLEE (1967, p. 3642). The fault gouge within the Lochseitenkalk is, therefore, considered evidence that the thrust *later* moved along a cohesionless plane by frictional sliding, after the limestone had fractured with a loss of cohesion.

TRÜMPY's analysis of the kinematics of the Glarus overthrust also suggested at least two phases of movement (personal communication, also TRÜMPY and HERB, 1962, p. 113). The main thrust was followed by the uplift of the autochthonous massifs, which resulted in the arching of the thrust plane and produced its present northerly

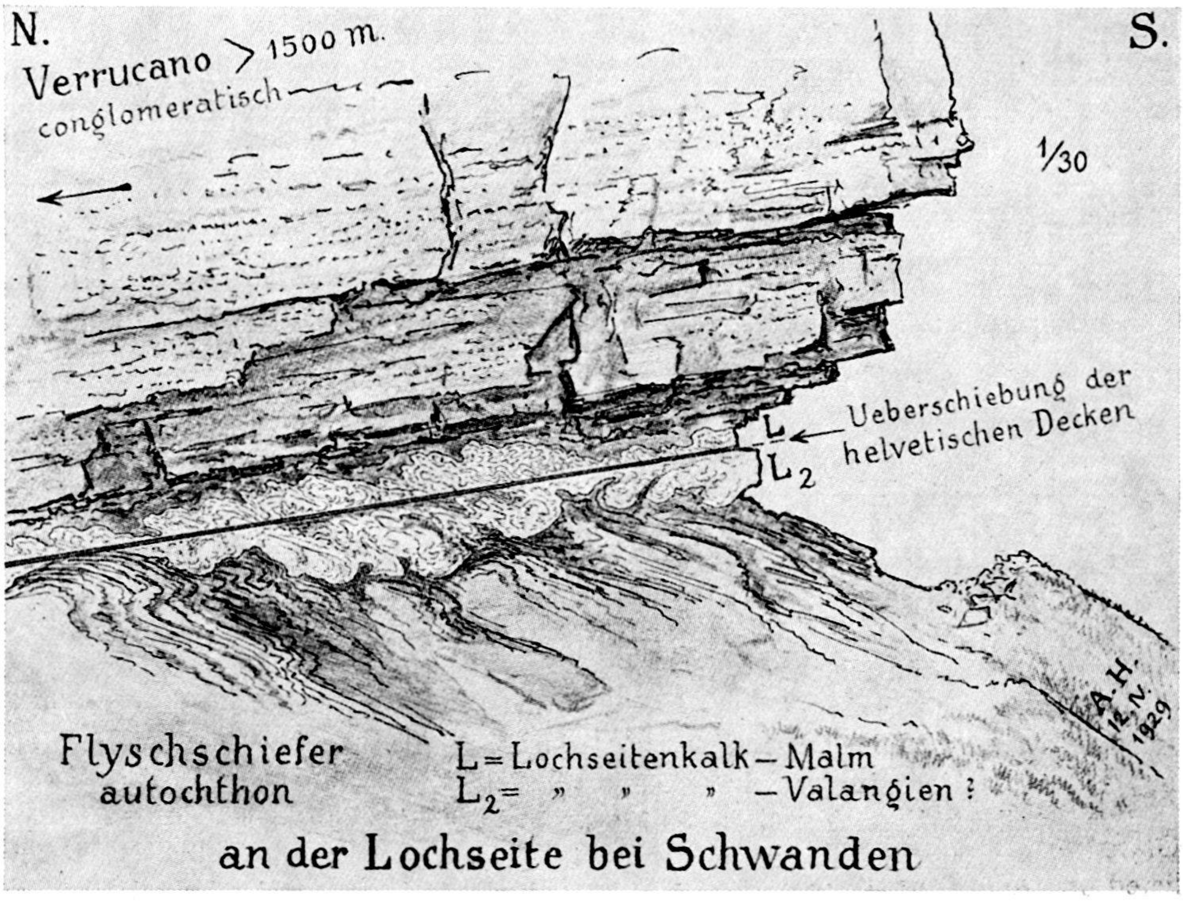

Figure 1 The thrust contact of the Glarus overthrust at Lochseite near Schwanden (Glarus), reproduced from ALBERT HEIM (1929).

dip of about 10 to 12 degrees. During the main phase the thrust plane should have been more nearly horizontal and its northerly dip probably did not exceed 5°.

The available evidence thus led me to assume

(1) an initial shear strength of $\tau_0 = 2 \times 10^8$ dynes/cm^2 and $\theta < 5°$ for the main phase when the thrust flowed, and

(2) an initial shear resistance $\tau_0' = 3$ to 10×10^7 dynes/cm^2 and $\theta = 10° - 12°$ for the later, and probably minor phase, when the thrust slid.

This leaves λ_1 as the most uncertain variable in equation (3). Field evidence alone cannot yield a numerical value. RUBEY and HUBBERT (1959) reasoned that geosynclinal sedimentation of flysch-type rocks inevitably led to the development of abnormal pore pressure; for example, a value of $\lambda_1 = 0.9$ was found in the deeper zones of Ventura Basin, California (HUBBERT and RUBEY, 1959, p. 154). The occurrence of a similar high pore pressure was certainly possible at the base of the Glarus overthrust. However, is it necessary for us to make such a postulate? If so, how high must the pore pressure be?

Table 1 lists the results of computations, assuming a thrust block of 35 km long, and 5 or 6 km thick, substituting the values of various constants into equation (3). The table shows the relation between the different assumptions of λ_1, θ and τ_0 (or τ_0').

When the Glarus overthrust was displaced by flowage along thrust plane, the value of $\tau_0 = 2 \times 10^8$ dynes/cm^2 should be substituted. The figures show that the pore pressure at the base of the Glarus overthrust must have been very high, say $\lambda_1 =$ 0.8–1.0, if the thrust moved down a slope of 5 degrees or less.

When the Glarus overthrust slid along a brittle fracture, a probable minimum value of $\tau_0' = 3 \times 10^7$ dynes/cm^2 should be substituted. The figures show that if the pore pressure was normal the minimum dip of the thrust plane would have to be 6°. Since the observed dip is 10°–12°, we do not need to assume abnormally high pore pressure for this later movement, although the pore pressure may have remained high, nevertheless.

Table 1 Minimum inclination of thrust plane, as a function of pore pressure – overburden pressure ratio λ_1 and of initial shear strength τ_0 (for $z_1 = 5$ or 6 km)

λ_1	$\tau_0 = 200$ bars $z_1 = 5$ km	$z_1 = 6$ km	$\tau_0' = 30$ bars $z_1 = 5$ km	$z_1 = 6$ km
0.465	14°	11°	6°	4°
0.5	13°	10°	5°	3°
0.6	11°	8°	2 1/2°	1°
0.7	8 1/2°	5°	0°	–1°
0.8	6°	3°	–2 1/2°	–4°
0.9	3 1/2°	1°	–5°	–6°
1.0	1°	–1 1/2°	–7 1/2°	–8 1/2°

A second question of interest concerns the probability of gravity sliding of the Glarus overthrust. The numerical results, computed on the basis of equation (4) and listed on Table 2, permitted some tentative conclusions:

(1) During the main phase of Glarus thrust when $\tau_0 = 2 \times 10^8$ dynes/cm^2, the minimum critical angle of gravitational sliding for a 6 km thick block would have

to be 8.3° under the extremely favorable condition of $\lambda_1 = 1$ (for a 5 km thick block, $\theta_c \simeq 10°$). The probable critical angle should be several degrees more because the obstructions in the front of such a thrust block, producing the so-called toe-effect (see RALEIGH and GRIGGS, 1961), has not been taken into consideration in my analysis. With the less extreme assumption of $\lambda_1 = 0.9$, the minimum angle would have to be 11.6°, and the probable angle some 20°, to cause gravity sliding. Since the thrust plane then dipped less than 5°, *the main movement along the Glarus thrust could not have been gravity sliding; a push from behind must be assumed.*

(2) During the second stage of the deformation, condition became more favorable for gravity sliding. Not only was the northerly dip steepened to 10° or more, also the cohesion had been eliminated when the thrust plate moved by frictional sliding along a pre-existing fracture surface. We should substitute a τ_0' value into equation (4). The results showed that gravity sliding was almost unavoidable if the pore pressure had remained very high. However, if the pore pressure had been reduced to $\lambda_1 = 0.7$ (still abnormally high), gravity sliding could not take place; then a push from behind would be necessary. Whether the Glarus overthrust did slide under its own weight during this phase must be decided by field evidence. Probably, the gravitational sliding along the Glarus thrust itself was minor, because of large pull-apart gaps are absent from the northerly dipping part of the overthrust. On the other hand, some higher tectonical elements may have slid away gravitationally during this phase of deformation (TRÜMPY, personal communication).

Table 2 Minimum angle (in degrees) of gravity sliding of a 6 km thick block as a function of pore pressure – overburden pressure ratio λ_1 and of initial shear strength τ_0

λ_1	τ_0=200 bars	100 bars	30 bars	0
0.465	25.1	22	18.4	17.2
0.6	21.1	17	14.2	13.0
0.7	18.0	14	11.1	9
0.8	14.9	10	7.8	6.6
0.9	11.6	7	4.6	3.3
1.0	8.3	3	1.3	0

The kinetics of the Glarus overthrust

Our knowledge of rock mechanics is so scanty that even a calculation on the order of magnitude of overthrust rate would seem foolhardy. Nevertheless, I am presenting the following analysis, based in part upon imperfectly known experimental relations, and involving a number of simplifying assumptions. The purpose of this attempt is to show that such computations are not impossible, and to explore the areas of experimentation necessary for refinement in our estimate. The rate of thrust movement by flowage will be treated first, followed by a discussion of the factors governing the rate of frictional sliding.

Rate of Overthrusting by Flowage

The proposed mechanism for the main phase of the Glarus overthrust might be compared to the sliding of one plate over another, with the upper plate being carried by the forward flow of a layer of pseudoviscous material (in this case, the Lochseitenkalk) between the plates. The rate of the movement could then be determined by the relation (Hsü, in press)

$$\frac{dx}{dt} = \frac{\tau}{\eta'} \cdot z_2 \tag{7}$$

where τ is the shearing stress inducing the pseudoviscous flow, η' the equivalent viscosity of flowing material and z_2 the thickness of the flow layer.

The thickness of Lochseitenkalk, z_2, could be taken as 1 m.

The magnitude of stress τ could be estimated from two different approaches. The minimal shearing stress must overcome the critical shearing resistance, which would be $2–3.6 \times 10^8$ dynes/cm² for a 6 km thick block, for λ_1 values of 0.8–1.0. The maximum permissible shearing stress could be stimated on the basis of the Laubscher (1961, p. 244) equation:

$$\tau_{max} = \frac{1}{x_1} \{a \cdot z_1 + [b + (1 - b)\, \lambda]\, \varrho_b \cdot g \cdot z_1^2\} \tag{8}$$

where λ is the value of pore pressure to overburden pressure ratio within the thrust block, and should not be smaller than the normal value of 0.465. Assumed $\lambda = 0.5$ and substitute $x_1 = 35$ km and $z_1 = 6$ km to equation (8), we obtained a maximum permissible stress of 3.6×10^8 dynes/cm².

The magnitude of η' is difficult to determine, because it is not a material constant, but varies with τ, and with temperature of deformation. Heard (1963, p. 182) suggested that the equivalent viscosity of marble in tectonically active regions of the crust may range between 10^{23} to 10^{16} poises! however, through the relation

$$\eta' = \frac{\sigma}{3\,\dot{\varepsilon}} \tag{9}$$

where $\dot{\varepsilon}$ is strain rate, which is itself a function of differential stress and of temperature T, the equivalent viscosity could be more closely estimated.

Yet the temperature of Glarus deformation is also uncertain. The rocks of the Glarus overthrust have been recrystallized in part; sericite and chlorite are present in the Verrucano formation. On the other hand, there is definitely no evidence of amphibolite facies metamorphism, which, according to Winkler (1968), started at 540°C and 2 kilobars pressure at $\lambda = 1$. It is reasonable to assume that the average temperature of deformation could not have been more than 500°C. Meanwhile, until a thorough study of the temperature of recrystallization of Lochseitenkalk is made, we could only use the trial-and-error method to estimate the temperature and strain rate.

Table 3 shows the computed strain rates and equivalent viscosities of limestone at a differential stress of 6×10^8 dynes/cm² (equivalent to the estimated τ_{max} of 3.6×10^8 dynes/cm² for the Glarus overthrust), based upon Heard's (1963, Figure 19) data on experiments of Yule marble, with the extension direction parallel to foliation.

Assuming a 300–500°C temperature of deformation, the equivalent viscosity of the Lochseitenkalk would range from 4×10^{15} to 1.3×10^{21} poises.

Substituting the estimated values of η', τ_{max}, z_2 in equation (7), the displacement rate of Glarus overthrust would be

$$10^{-3} \text{ cm/yr. at } 300°\text{C}$$

or

$$2 \text{ cm/yr. at } 400°\text{C}$$

or

$$3 \times 10^2 \text{ cm/yr. at } 500°\text{C}.$$

Table 3 Estimated strain rates and viscosities (in poises) of limestone as a function of temperature ($\sigma = 6 \times 10^8$ dynes/cm^2)

Temperature	300°	400°	500°
$\dot{\varepsilon}$	1.5×10^{-13}	3×10^{-10}	5×10^{-8}
η'	1.3×10^{21}	6×10^{17}	4×10^{15}

We can rule out the lowest rate estimate (at 300°C) because such a slow strain rate would lead to the absurdity that it took 3 billion years for the Glarus overthrust to move 30 km.

The highest estimate can also be ruled out, not only because 500°C seems to be too high as an assumed temperature of deformation, but also because the implication of the result is inconsistent with original assumption, when we considered thc relation between temperature and power output (work rate):

The heat production rate per unit area Q_p as a result of the mechanical work of overthrusting (assuming no changes in energy content of the rocks within the thrust zone) is

$$Q_p = \frac{\text{Total work performed per unit area W/A}}{\text{Total duration of thrusting, } t} \tag{10}$$

Since $W/A = \tau \,.\, d = 15$ ergs/cm^2 (or 2.2×10^7 cal/cm^2) for d (thrust displacement) = 30 km, the computed Q_p would be 7×10^{-5} cal/cm^2 s., if the thrust was completed at $t = 10^4$ years (at 3×10^2 cm/yr rate). Such a Q_p value would not only give an absurdly high surface heat flow, 60 times the normal, but also lead to a temperature estimate at 6 km depth much higher than the 500°C assumed for this strain rate.

This would leave the estimate of a displacement rate of 2 cm/yr at 400°C as more nearly correct. The estimate is comparable to some actualistic examples of fault displacement rate: The San Andreas fault moved locally at an average rate of 0.5 cm/yr and a maximum of 1.4 cm/yr (BURFORD, 1966), and the Buena Vista thrust moved about 5 cm/yr (GILLULY, 1949).

We can compare this estimate with the probable minimum and maximum rates of Glarus overthrusts determined from two independent approaches.

The minimum rate is determined by geologic deductions. TRÜMPY (personal communication) found evidence that the main phase of the Glarus thrust occurred during the Miocene, or the thrusting should have been completed within 15 million years. This represents a minimum rate of 0.2 cm/yr.

The maximum rate is based upon a consideration of the possible heat production as a result of thrusting. The reasoning is based upon the fact that the surface heat flow variations in non-volcanic areas are limited. The heat flow in tectonically active areas may be twice as high as the norm of 1.2 μcal/cm^2 s, but rarely more than thrice (LEE and CLARK, 1966). An application of the uniformitarian principle would suggest that heat production rate by overthrusting (Q_p) should not be greater than 2 μcal/cm^2 s. According to equation (10) heat would be produced at this rate, if the Glarus overthrust should have been completed in 3×10^5 years, moving at a maximum rate of 10 cm/yr. Furthermore, we may estimate the temperature of thrusting through the relation

$$T = T_0 + R\,(Q_b + Q_p)\,z_1 \qquad (11)$$

where T_0 is the surface temperature and could be taken as 10°C, and R the thermal resistivity which for limestones and water-saturated sandstones may range from 150 to 200 cm s °C/cal (CLARK, 1966). The estimated maximum Q_p plus the normal heat flow from the mantle source Q_b (of 1.2 μcal/cm^2 s) would give a temperature of 300° to 400°C at 6 km depth.

To recapitulate I would like to point out that I assumed only a knowledge of thrust dimensions (x_1, z_1) and some experimentally determined constants in my computation on kinetics. The six unknown factors are rate of thrusting dx/dt, stress τ (or σ), strain rate $\dot{\varepsilon}$, equivalent viscosity η', temperature T, and mechanical heat production rate Q_p, related by the six relations:

$$f\left(\frac{dx}{dt},\ \eta',\ \tau\right) = 0 \quad \text{equation (7)}$$

$$f(\tau, x_1, z_1) = 0 \quad \text{equation (8)}$$

$$f(\sigma, \eta', \dot{\varepsilon}) = 0 \quad \text{equation (9)}$$

$$f(\eta, \dot{\varepsilon}, T) = 0 \quad \text{(HEARD, 1963)}$$

$$f\left(Q_p, \frac{dx}{dt},\ \tau\right) = 0 \quad \text{equation (10)}$$

$$f(Q_p, T, z_1) = 0 \quad \text{equation (11)}\,.$$

The solution led to an estimated displacement rate of 2 cm/yr at a deformation temperature of 400°C, on the basis of strain rate considerations, and a maximum displacement rate of 10 cm/yr at a deformation temperature of 300° to 400°C on the basis of heat budget considerations. A temperature of 400°C seems to be higher than expected, judging from the largely unmetamorphosed nature of the Flysch under the thrust, and the error may have resulted from our imperfect knowledge of the relation among η', $\dot{\varepsilon}$ and T.

Rate of Overthrust by Frictional Sliding

Gravitational sliding along pre-existing fractures would lead to catastrophic sliding, moving at speeds of many meters per second, if the sliding was not checked after a short displacement (HSÜ, in press). The fact that many faults which apparently moved by frictional sliding did not develop into catastrophic slides could be attributed to two causes: either the faults slid as 'stick-slips', or the faults were checked by the 'toe' effect.

The term 'stick-slip' was used by BRACE and BYERLEE (1966) to describe jerky sliding along a fault surface. For a thrust that was pushed from behind, the stress was increased until a fault formed. If the fault resulted in a brittle fracture, a small slip along the fracture surface would result in a large stress drop. Stress could then be built up again if the push from behind continued. After the build-up reached a certain level, there would again be displacement and a sudden stress drop. This jerky sliding could be continued as long as stress could be built up continuously.

Stick-slip has been observed experimentally, and shallow-focus earthquakes have been interpreted as stick-slip along shallow faults (BRACE and BYERLEE, 1966). The rate of short displacement is sudden and could be measured in terms of cm/s. However, the average rate of accumulative fault displacement depends upon the rate of stress-build-up. In case the late-phase frictional sliding along Glarus thrust was caused by a push from behind, the effective rate of its movement should be determined from the rate of the push, and may be cm/yr or slower if the push was applied by an advancing nappe.

The term 'toe effect' was applied by RALEIGH and GRIGGS (1963) to denote the obstruction in front of advancing overthrust. They reasoned that 'a large moving thrust plate must somewhere along its length shear off and ride up over a stationary block of rock'. The frontal part which must be pushed up has been called the 'toe'. The toe increases in size as the thrust advances so that the gravity-sliding movement of a thrust would be stopped after a short displacement, when the 'toe' effect overcomes the critical shearing stress. Further sliding would only be possible after the size of the toe has been reduced by erosion. The average rate of thrust displacement would, therefore, be governed by the rate of erosion. The individual movements, however, must have been similar to stick-slip, characterized by sudden and jerky frictional sliding.

Summary

This paper is a preliminary treatise of the statics and kinetics of the Glarus overthrusts applying the general principles I developed in an earlier work. The tentative conclusions are as follows:

(1) The Glarus overthrust has a dimension of 35 km long and about 5 to 6 km thick.

(2) The overthrust took place in two phases at least: the earlier phase of main movement was related to the flowage of the Lochseitenkalk within the thrust zone, and the later phase of frictional sliding produced the thin film of fault gouge within the Lochseitenkalk.

(3) The earlier movement was related to a push from behind along a nearly horizontal thrust plane, where the pore pressure was equal, or nearly equal, to the overburden pressure.

(4) The later movement was probably related to an uplift of the autochthonous massif, which produced the present 10° to 12° northerly dip of the Glarus overthrust. If the pore pressure had remained abnormally high, the block would have to slide under its own weight. If the pore pressure had dropped to normal, then a push from behind would be necessary.

(5) The rate of the earlier displacement through the flowage of Lochseitenkalk could be estimated as to range from 0.2 to 10 cm/yr with a temperature of 300–400°C at the base of the thrust (6 km depth). Heat generated by overthrusting may have contributed to the steep geothermal gradient then prevailing in the Glarus region.

(6) The rate of later displacement by frictional sliding was governed either by the rate of stress build-up as a result of the push by an advancing nappe from behind, or by the rate of erosion of the toe which obstructed gravity-sliding. In either case, the displacement would be jerky sliding, resulting in a series of shallow earthquakes.

Refinements of this preliminary study depend upon a better knowledge of the temperature at the base of the Glarus overthrust, to be obtained through a research of the metamorphic changes of the Glarus rocks, and a more precise knowledge among strain rate, stress and temperature, based upon experimental creep tests of the Lochseitenkalk. We hope to carry out the first of these two proposed researches at Zurich in near future.

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