The Clay Consolidation Problem and Its Implications for Flood Geology Models

Scott L. Dunn*

Abstract

The cornerstone assumption of all Flood Geology models is that rocks can form quickly (i.e., within the timeframe of months to years). However, to date, only isolated examples from the field have been used to support the hypothesis without any quantitative justification. This paper therefore presents the theoretical basis (originally set out by Terzaghi, 1922) for determining the timescales for the first phase of lithification, the mechanical compaction of the sediment under its self-weight (otherwise known as consolidation). The paper demonstrates that when basic soil mechanics theory is applied to the consolidation of thick clay layers of the order of 1,000 m such as those found in the North Sea, Gulf of Mexico, and the Caspian Sea, the timescales predicted for compaction are orders of magnitude greater than is currently assumed. Additionally, it is shown that there is a physical limit to the rate at which sediment can accumulate without creating excessive pore pressure and inducing geotechnical failures. For clay, this limit is approximately 0.1 m/yr, and, for silt, approximately 10 m/yr.

Key Words: clay, consolidation, lithification, pore pressure, sand, shear strength, silt

Introduction

Over the last sixty years since the publishing of *The Genesis Flood: The Biblical Record and Its Scientific Implications* by Whitcomb and Morris (1961), numerous models have been proposed for how the Flood of Genesis, Chapters 6 to 8, may have been responsible for the presence of sedimentary rock layers around the world. These models have attempted to explain the formation of features such as the Grand Canyon, continental shelves, and the large volume of sedimentary rocks found on the continents. However, to date, it appears that no study has ever been carried out to quantify the timescales involved in the processes that cause the lithification of the sediment or to show that they are possible within relatively short geological timescales (i.e., within tens to hundreds of years).

Klevberg and Oard (2023) have recently highlighted the lack of quantitative models present in the Flood-Geology literature. They rightly point out that "there is a need to develop an effective model of sedimentary lithification to be used in a Flood model. To be useful, a lithification model must be more than speculation about natural

* Dr. Scott L. Dunn, Senior Technical Director, Jacobs, UK, sdunn74@yahoo.co.uk
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history; it must be as quantitative and empirical as possible." Although their paper provides very helpful descriptions of the processes involved in lithification, it does not provide the equations required to quantify the timescales involved. It is also focussed primarily on the processes relating to the lithification of sand rather than clay which is known to involve much longer timescales.

Field examples of rapid, sedimentary rock formation are usually limited to unique field environments. For example, the formation of beachrock which is typically 0.5 m to 2 m in thickness can form within months. However, it is only found on beaches with specific ranges of sand size, tidal range, wave climates, and water temperatures (Vousdoukas et al., 2007). It is also only found in a limited area in the inter-tidal zone. Similarly weak rock formations can form rapidly during pyroclastic flows from volcanic eruptions as observed in the 1980 Mt. St. Helens eruption. However, the conditions within pyroclastic flows involve very high temperature (>300 °C) and are almost entirely dry (water vapor content less than a few percent). In both these cases it is difficult to see how either of these examples are transferrable to the normal processes of lithification in marine deposits that make up the majority of the sedimentary layers.

This paper therefore attempts to present the framework for assessing the consolidation of clay under self-weight which is generally accepted to occur prior to any significant cementation. Although the focus is on clay due to its extremely slow drainage characteristics, the equations are valid for all sediments from sands to clays. The theory is drawn from basic soil mechanics which has been applied for over one hundred years in the engineering community and is commonly used for the design of dam, bridge, road and building foundation design.

Description of the Mechanisms for the Consolidation of Clay

When cohesive sediment falls out of suspension, it flocculates and deposits in an almost fluid-like state. It then slowly dewaters until it reaches a concentration where it behaves more like a soil than a fluid. This point is sometimes known as the gel point. In simple terms this is the transition from a mud to a clay and could be taken as the starting point of the consolidation phase where the material would be classified as having soil-like behavior.

At this point, when the gel point is reached and soil behavior commences, the clay is still extremely soft (consistency of toothpaste) and has a very high-water content compared to solid content. It is common for very soft clays to have porosities (i.e., the ratio between the volume of the voids to the total volume) in excess of 0.9. That means that more than 90% of the volume is comprised of voids filled with water and only 10% are clay particles. Typically, cementation in clay only occurs once the porosity is less than approximately 0.4 to 0.5. This highlights the enormous volume of water that must be expelled from the clay prior to cementation.

As an example, a 10 m deposit of very soft clay with a porosity of 0.9 would need to compact to a thickness of 2 m to have a porosity of 0.5 (2 m = 10 m * (1–0.9)/(1–0.5)). Once cementation begins additional compaction can occur giving rise to further reduction in the layer thickness. For example, it is not uncommon for claystones to have porosities of less than 0.25. This would give rise to a thickness of 1.33 m. Therefore, 10 m of freshly deposited soft clay is required to form 1.33 m of claystone.

Consolidation of cohesive sediments has been an area of extensive geotechnical research for over 100 years. Figure 1 shows the basic principles of consolidation where the soil matrix is modeled as a spring and the pore water must escape in order for the spring to compress. The initial load is transferred directly to the water generating excess pore pressure (i.e., greater than hydrostatic pressure). This high pore pressure then begins

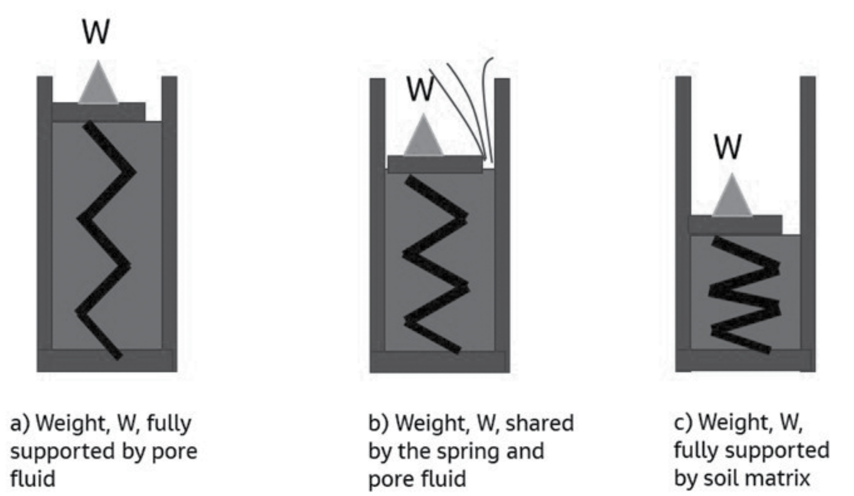

Figure 1. Three stages of consolidation: a) Initial loading where the load is transferred directly to the fluid (no load in the soil spring); b) load transfers from the fluid to the soil spring as water escapes; c) End of consolidation when all the load is now carried by the spring and no flow of water out of the soil

to squeeze water out of the soil at a rate controlled by the permeability (or hydraulic conductivity) of the soil. As the water volume reduces the load is transferred to the soil and it begins to compact.

Simple Analytical Solution of Consolidation Process (Terzaghi's Principle)

The principles for calculating the rate of consolidation of soil were first developed in the 1920s by Terzaghi (Terzaghi, 1922). These were initially based on assumptions of relatively small settlements (infinitesimal strains) but have proved to be adequate for most engineering problems and are still in use today. For cases where the consolidation is substantial (e.g., the consolidation of tailings dam soils), more detailed numerical methods are required (as described in the following section). However, the general principals of consolidation are well described by Terzaghi's equations set out below.

The governing equation that relates the dissipation of the excess pore pressure (U, kPa) to the coefficient of consolidation, c_v (m^2/s) is given by:

$$\frac{\partial U}{\partial t} = c_v \frac{\partial^2 U}{\partial z^2} \quad (1)$$

$$\text{where } c_v = \frac{K}{m_v \gamma_w} \quad (2)$$

m_v is the coefficient of volume compressibility and has units in m^2/N and is a measure of how compressible the material is for a given load. Here low values of m_v represent a "soft" soil which has a higher potential for compression. The hydraulic conductivity, K (m/s), is a measure of the permeability of the soil where low values (such as in clays) results in smaller rates of pore pressure dissipation and hence longer periods for consolidation (see Table I). The excess pore pressure, U, is the pressure above normal hydrostatic pressure.

Table I. Typical range of hydraulic conductivity, *K*, for different soil types (from Freeze and Cherry, 1979).

	Typical range of hydraulic conductivity, *K* (m/s)
Gravel	10^{-2} to 10^{-1}
Sand	10^{-5} to 10^{-3}
Silt	10^{-8} to 10^{-6}
Clay	10^{-11} to 10^{-9}

As can be seen the governing equation has the familiar form of a diffusion equation. This is therefore analogous with common diffusion problems such as heat diffusion. The coefficient of consolidation, c_v, in Equation 1 is similar to the heat diffusivity property of materials. The time taken to heat up a sample is proportional to the length scale of the object squared and inversely proportional to the heat diffusivity. Similarly, the time it takes for clay to consolidate is proportional to the thickness of the sample squared and inversely proportional to the coefficient of consolidation.

Equation 1 can be simplified to the well-known expression (Terzaghi's principle):

$$t = \frac{T_v H^2}{c_v} \quad (3)$$

Where t is the time for consolidation to occur and H is the drainage length. For a one-way drainage (i.e., impermeable bottom) the value of H is the same as the soil thickness.

T_v is a time constant related to the percentage complete of the consolidation process. For example, the time factor for 90% of the consolidation to complete is 0.85. Likewise for 50% consolidation to complete the time factor is 0.19. This demonstrates that the latter stages of consolidation take much longer than the early stages. It takes 4.5 times longer to reach 90% completion than 50%.

The time t is therefore proportional to the thickness of the layer squared and inversely proportional to coefficient of consolidation (and consequently the hydraulic conductivity, K, via Equation 2). The importance of these relationships is demonstrated in Tables II and III where the time to attain 50% and 90% consolidation has been derived for different soil types of varying thicknesses. Typical values of the coefficient of consolidation, c_v, have been given for each soil type based on experimental values presented by Shridharan and Nagaraj (2004) (see Figure 2).

As can be seen there is an enormous range in the predicted consolidation durations depending on the soil type and thickness. In normal civil engineering practice soft clay layers of thicknesses of 5 m to 10 m are usually unsuitable for foundations due to the large settlement times (i.e., greater than 10 years). Therefore, it is common to either use piled foundations or introduce alternate drainage pathways (e.g., wick drains) to speed up the consolidation process.

Of most note, however, are the extremely long timescales required to consolidate very thick clay layers. Time scales in excess of one million years (Myr) would be predicted by the Terzaghi equation for clay thicknesses of 1,000 m or more. There are many sedimentary basins which have thicknesses of this or-

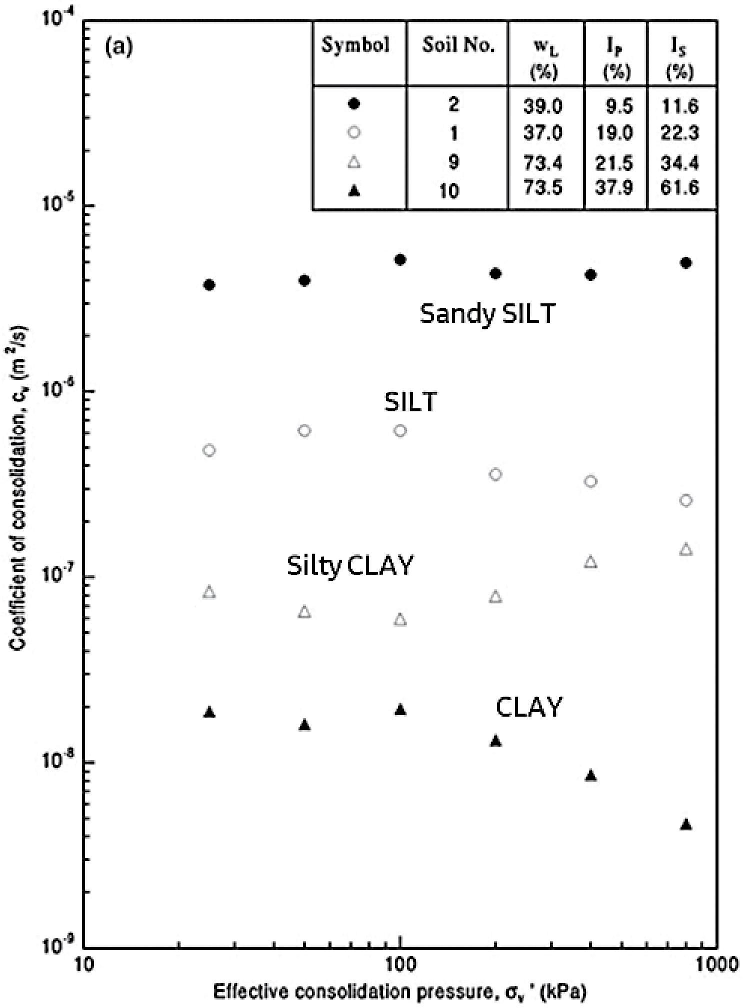

Figure 2. Typical values of coefficient of consolidation, c_v, (from Sridharan and Nagaraj, 2004).

der and even greater such as the Gulf of Mexico, the Caspian Sea, the Labrador Sea and the North Sea.

Klevberg and Oard (2023) provided an example of the duration involved in the consolidation of clay based on experiments carried out for a lithification pilot project. The pilot study was conducted on a sample of fat clay approximately 6 inches high (15.25 cm) and involved applying approximately 6 MPa confining pressure (equivalent to 300 m of overburden). After approximately 6 months of loading the clay sample had undergone sufficient compaction to reach the borderline of unlithified sediment and rock. Using Equation 3 estimates for consolidation can be made for field scale thicknesses of clay. If the same experiment was carried out on a 100m thick layer of similar clay in the field and subjected to the same loading of 6 MPa, the time for consolidation would be over 200,000 years. This highlights the crucial role that the thickness of the layer plays in controlling consolidation times. It is not clear that previous Flood Geology models had accounted for this.

Detailed Numerical Modelling of Deposition and Consolidation

Some of the limitations of the simple analytical method presented in in the previous section are that it assumes that the settlement is relatively small compared to the thickness of the layer and that the coefficient of consolidation remains constant throughout the settlement process. In order to assess a typical Flood Geology scenario where very large consolidations occur (i.e., transformation from very soft clay to very firm clay or rock), a model is required that can account for these large changes in both the thickness of the layer and any potential change to the coefficient of consolidation during the process.

The present author has developed a finite difference model based on a similar methodology to that presented by Jeeravipoolvarn et al. (2008). The vertical one-dimensional governing equation for the dissipation of the excess pore pressure, U, and the development of the vertical effective stress, σ', is given by:

$$\frac{1}{(1+e_0)^2}\frac{\partial U}{\partial t} + \frac{\sigma'^{(1-B)}}{AB\gamma_w}\frac{K}{1+e}\frac{\partial^2 U}{\partial z^2} + \frac{\sigma'^{(1-B)}}{AB\gamma_w}\frac{\partial\left(\frac{K}{1+e}\right)}{\partial z}\frac{\partial U}{\partial z} = 0 \quad (4)$$

Where e is the void ratio and e_0 is the initial void ratio. Parameters A, B, C and D are laboratory determined parameters such that:

$$e = A\sigma'^B \quad (5)$$

$$K = Ce^D \quad (6)$$

It should be noted that the expression in the first term is missing from the equation in Jeeravipoolvarn et al. (2008). However, it does appear that it was included in their actual simulations.

Figure 3 shows the validation of the model against a 10 m-high standpipe test for a material which was 45% clay, 45% silt and 10% sand as reported in Jeeravipoolvarn et al. (2008). The material properties for the model were the same as those used by Jeeravipoolvarn et al. (2008).

A = 3.391
B = -0.308
C = 6.51.10^{-6} m/day
D = 3.824

The specific gravity, S_g, of the material was 2.28 and the initial void ratio, e_0, was 5.17 (equivalent to a porosity of 0.84). These set of parameters produce an average value for the coefficient of consolidation c_v = 1.10^{-8} m^2/s which is typical for a silty clay.

The model gives a very good representation of the settlement over the first 10 years but tends to overestimate the rate of consolidation for the second 10 years. This suggests that these methods may underestimate the time for consolidation. It can be seen, however, that even after 20 years, the material is still consolidating despite having settled nearly 30% of its original height.

By way of comparison with the simple method presented in the previous section, the time required to achieve 50% consolidation for a material 10 m thick and an average coefficient of consolidation of c_v = 1.10^{-8} m^2/s is given by: $T_{50\%}$ = 0.19 * 10 m * 10 m / 1.10^{-8} m^2/s = 60 years. This is a similar order of magnitude as the more detailed numerical model showing that the simple Terzaghi model (Equation 3) provides a good first estimate of the likely time for consolidation.

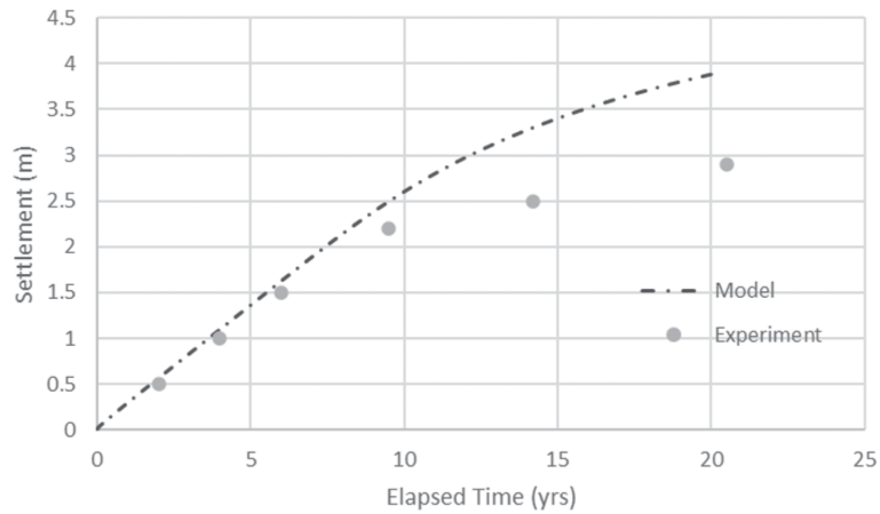

Figure 3. Validation of numerical model against 10 m-high test facility at University of Alberta (Jeeravipoolvarn et al. 2008).

Application of the Numerical Model to a Typical Thick Clay Deposit (Labrador Sea)

In 1985, a number of deep boreholes were drilled in the Labrador Sea off the coast of Greenland as part of the Leg 105 campaign. Holes 646A and 646B were drilled in approximately 3,500 m water depth (borehole location shown in Figure 2). Hole 646B was drilled to 766.7 m below the sea floor. The upper unit is predominantly a silty clay (0 to 188.2 m below sea floor). The lower unit II is composed of claystone and siltstones (see Table II for a description of the lithology). A full description of the field work is presented in Arthur et al. (1985).

The deposits are fairly recent and are described as being late Miocene to Holocene (i.e., the last 10 million years in geological terms). In flood models, this would be placed either entirely post-Flood or right at the end of the Flood.

The variation of the porosity (volume of pores/total volume), density, and sand/silt/clay content of the strata is shown in Figure 6. This shows a number of key features:

a) A relatively uniform grading of material with very little sand over the entire depth and a relatively consistent split of silt to clay (40% silt to 60% clay).

b) A consistent reduction of porosity from 0.85 (at seabed level) to 0.4 at depth apart from the nonconformities at 130 m and 330 m below the sea floor.

For the numerical model described in the previous section, the input parameters the values of A, B, C, and D have been chosen to match those of typical silty clay such that:

A = 5.5
B = -0.22
C = 1.10^{-7} m/day
D = 6.0

The values of A and *B* were derived directly from consolidation tests reported in Dadey and Silva (1989) (Figure 6).

This results in a relatively constant coefficient of consolidation, c_v, of 5.10^{-7}m^2/s over the full range of effective stresses which is within the typical range for a silty clay to clay (Figure 7).

In addition to the consolidation aspects of the model, an additional feature to allow deposition has been included. This allows the model to add new layers of material at a designated interval. As the height of the layer of sediment increases, it also consolidates. In cases where the deposition is fast, and the

Table II. Estimate of time to reach 50% consolidation for varying soil types and thicknesses.

	Coefficient of consolidation (m^2/s)	Estimate to reach 50% consolidation (years)		
		10 m-thick layer	100 m-thick layer	1,000 m-thick layer
Fine sand	10^{-4}	0.006	0.6	60
Silty sand	10^{-5}	0.06	6	600
Silt	10^{-6}	0.6	60	6,000
Silt clay	10^{-7}	6	600	60,000
Clay	10^{-8}	60	6,000	600,000
Calcareous ooze	10^{-7}	6	600	60,000

rate of consolidation is slow, the pore pressure increases. This is similar to the processes currently observed in deltaic deposits such as the Ursa Basin in the Gulf of Mexico (Flemings et al., 2012) where the build-up of pore pressure is responsible for large-scale slope failures leading to mass-transport deposits.

The model can also be used to model the development of the shear strength of the clay as the pore pressure dissipates and the material hardens. A typical value for the undrained shear strength, c_u (kPa), can be derived from the effective stress, (kPa), using the following simple relationship:

$$c_u = 0.2\sigma' \quad (7)$$

Typical descriptions of the strength of clay are shown in Table IV.

Another important parameter for tracking the consolidation process is the so-called overpressure ratio, λ^*. This is given by the formula:

$$\lambda^* = U / (U+\sigma') \quad (8)$$

When $\lambda^* = 0$, all of the excess pore pressure has been dissipated, and the fluid is in hydrostatic conditions. This would be the scenario for dissipation over an infinite amount of time. On the other hand, $\lambda^* = 1$ represents the case when the effective stress between the grains is zero. In this scenario the soil is completely fluidized or liquefied and the solid particles are "floating" in the soil. At this point the soil has no strength and behaves as a fluid. This commonly occurs in loose sands during earthquakes when the pore pressure builds up due to shaking of the soil and reaches a state where the sand liquefies. In clays, high pore pressure prevents the soil strength increasing, and it remains in a fluid-mud situation.

It is common to observe very high overpressure ratios in deltaic areas

Table III. Estimate of time to reach 90% consolidation for varying soil types and thicknesses.

	Coefficient of consolidation, c_v (m^2/s)	Estimate to reach 90% consolidation (years)		
		10 m-thick layer	100 m-thick layer	1,000 m-thick layer
Fine sand	10^{-4}	0.027	2.7	270
Silty sand	10^{-5}	0.27	27	2,700
Silt	10^{-6}	2.7	270	27,000
Silt clay	10^{-7}	27	2,700	270,000
Clay	10^{-8}	270	27,000	2,700,000
Calcareous ooze	10^{-7}	27	2,700	270,000

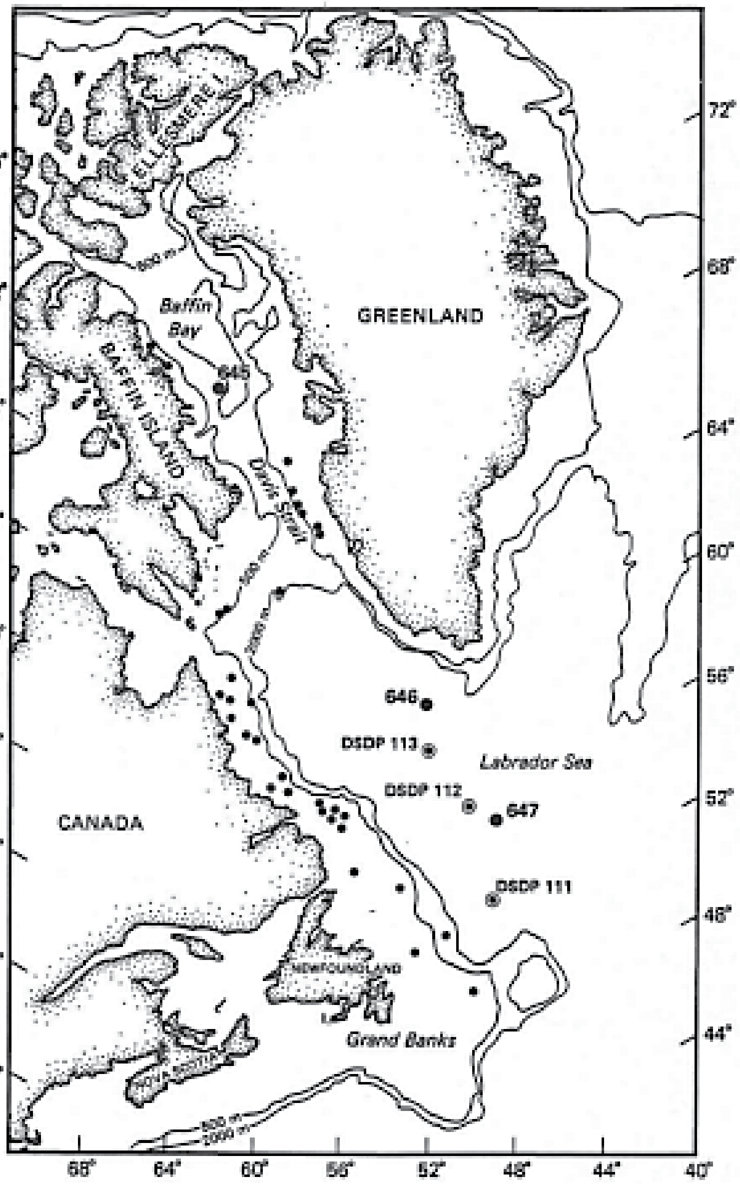

Figure 4. Location of drill site 646 in the Labrador Sea with water depth of 3,500 m (from Arthur et al.,1985).

where sedimentation rates are known to be high. Sawyer et al. (2009) and Flemings et al. (2012) presented measurements of porosity and pore pressure from the Ursa Basin on the Gulf of Mexico continental slope and demonstrated that there was a very high risk of submarine landslides when $\lambda^* > 0.7$ in clay deposits. This is evidenced by the widespread occurrence of mass transport deposits (MTDs) which are easily recognizable in the sediment strata via geophysical surveys.

Therefore, when assessing the results of the numerical model values of $\lambda^* > 0.7$ would be considered likely to produce slope failures and to be unstable for slopes steeper than 1.5°. Values of $\lambda^* > 0.9$ are likely to be unstable for very flat slopes of < 1°.

Scenario 1—Flood deposit hypothesis (deposition in 100 days)

This scenario represents the case where all the material is deposited during the Flood. Given that lower strata are probably also assumed to have been deposited earlier in the Flood, this represents a conservative estimate of the duration over which to calculate an average deposition rate. It also assumes that the underlying strata have already hardened and hence the flow of the escaping pore water is upwards. It also assumes that the layers are relatively horizontal, and that the horizontal component of the pore-water flow is negligible.

Looking at the borehole records, we could assume an average porosity of 0.55 over the 770 m depth (Figure 5). This represents a total mass of clay (excluding the pore water) of:

Total mass of clay = (1–0.55) * 2650 kg/m^3 * 770 m = 918225 kg/m^2

The value of 2650 kg/m^3 is the assumed density of the clay particles.

Using this value, the average deposition rate over 100 days is 0.106 kg/m^3/s. It should be noted that this value is almost two to three times higher than the maximum mass settling flux observed in the field (see Winterwerp, 1999; Soulsby et al., 2013).

The model adds this mass at an initial concentration of 300 kg/m^3 which equates to a porosity of 0.89 (initial void ratio of 7.8). This is a typical value for the starting point of consolidation of predominantly clay materials. In reality the transition from a fluid mud of concentration 50 kg/m^3 to a very weak clay of concentration 300 kg/m^3 make take place over the course of weeks. However, this period has been neglected in the study due to its relatively fast timescales.

Figure 8 shows how the properties of the deposited clay develop with time. The curves are plotted for three specific times: 1 year after the commencement of deposition, 100 years after, and 10,000 years after. The following observations are made:

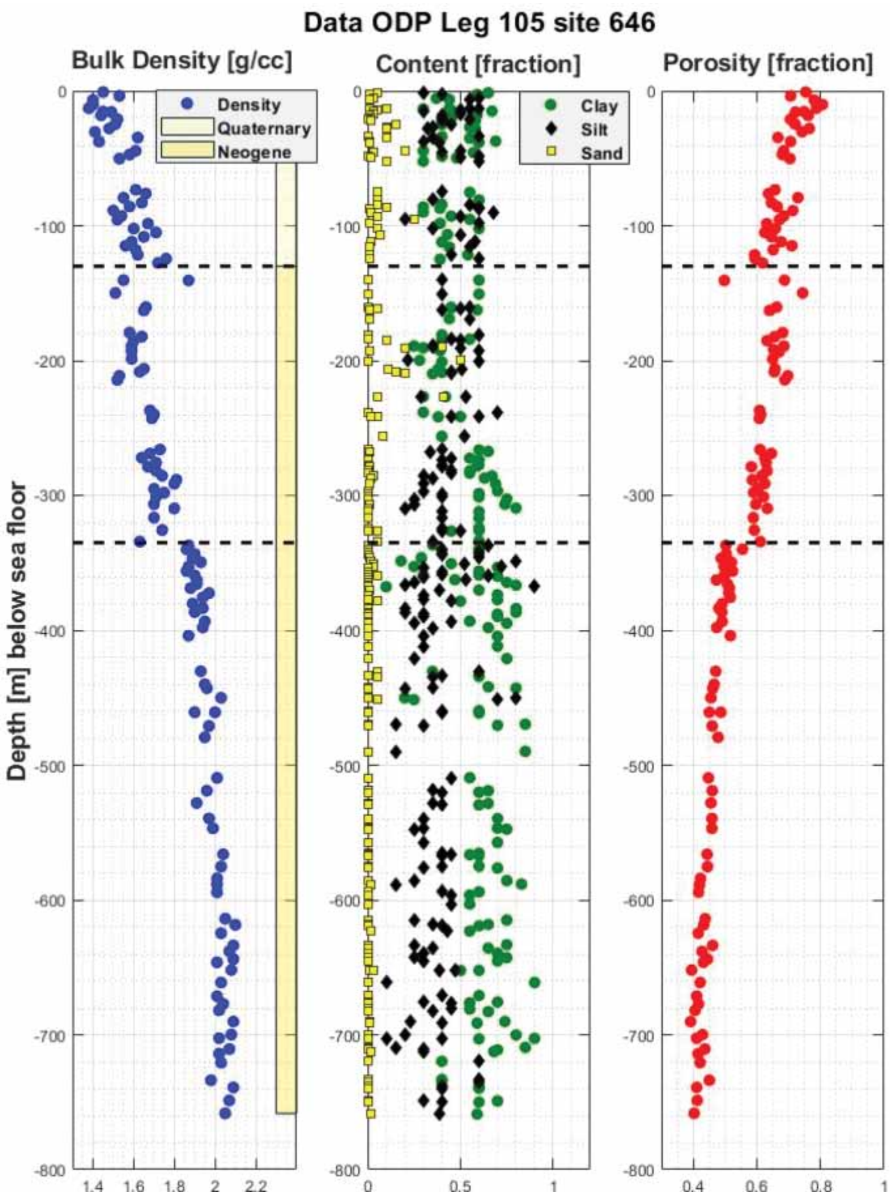

Figure 5. Summary of bulk properties from borehole 646B (from Orozova-Bekkevold and Petersen, 2021).

- After 1 year, there is practically no consolidation of the clay and the full 3100 m is still in its original deposited state (consistency of a thick slurry unable to carry any loading)
- After 100 years, approximately 1200 m of consolidation has taken place. However, there is still almost no reduction in the overpressure ratio or any gain in strength. The soil will still be in a practically fluidized state.
- After 10,000 years, the strength of the lower 100 m has increased to that of a low-strength clay (between 20 to 40 kPa). The settlement has increased to 1800 m.

Scenario 2—Post-Flood deposit hypothesis (deposition in 100 years)

In this case, the same volume of sediment (900,000 kg/m^2) is deposited over 100 years and then allowed to consolidate. This is similar to some of the post-Flood deposition hypotheses which postulate that some of the more recent deposits (Cenozoic, last 66 million years) are due to post-Flood deposition that may have occurred as the world established its current day state after the cataclysm of the Flood. Those that hold this view suggest that there was still a high rate of cataclysmic events for a few hundred years after the Flood (i.e., residual catastrophism during the first half of the post-Flood “Ice Age”) that could have produced deposits such as those of the Labrador Sea.

As with Scenario 1, sediment is added to the model at a concentration of 300 kg/m^3 and therefore ignores the hindered settling phase. The sediment is added at a uniform rate of 24.6 kg/day/m^2.

As can be seen from Figure 9, the results after 100 years and 10,000 years are similar to those from Scenario 1. Again, the shear strength of the clay after 10,000 years is still very soft over the top 1000 m and only gains low-to-medium strength in the bottom 100 m. The reason for the similarity with Scenario 1 is because the deposition rate is still much higher than the rate of settlement.

Scenario 3—Slow deposition hypothesis (deposition over standard geological time of nine million years)

The traditional geological understanding of the Labrador Sea deposits is that they formed over a period of approximately nine million years with an average deposition rate of 80 m/Myr (see Srivastava et al., 1987).

The results of the analysis for this scenario are shown in Figure 10. This shows that the undrained shear

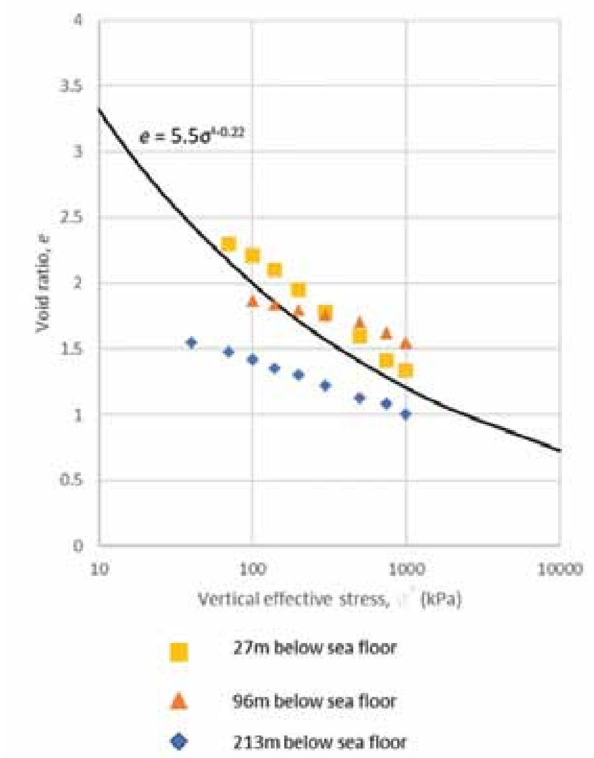

Figure 6. Void ratio vs. logarithmic effective stress (fitted curve vs. experimental data at three depths for borehole 646B).

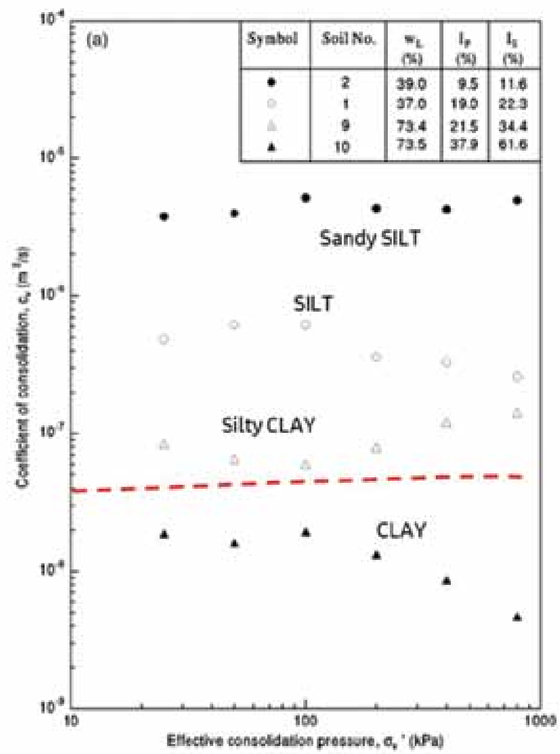

Figure 7. Modeled coefficient of consolidation, c_v, compared with experimental values (from Sridharan and Nagaraj, 2004).

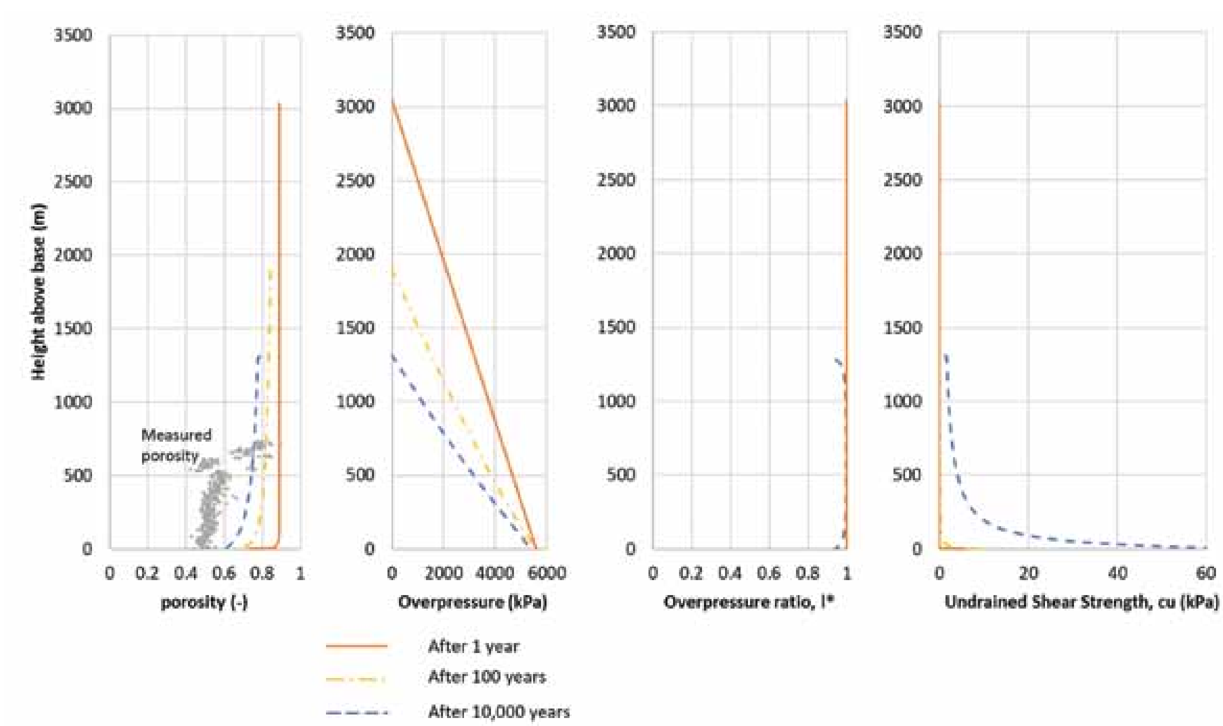

Figure 8. Scenario 1 (Flood deposition in 100 days).

Table IV. Typical definitions of clay strength (from Table V. British Standards BS EN ISO 14688-2).

Description of Clay	Undrained shear strength c_u (kPa)
Extremely low	<10
Very low	10 to 20
Low	20 to 40
Medium	40 to 75
High	75 to 150
Very High	150 to 300
Extremely High*	>300

* Materials with shear strength greater than 300 kPa may behave as weak rocks and should be described as rocks according to ISO 14689-1.

strength has developed to a point that the lower 400 m would be characterized as rock (i.e., c_u >300 kPa) and is consistent with the borehole logs which characterized the bottom 400 m as either siltstone or claystone. The total thickness is estimated to be approximately 730 m which corresponds with the measurement of 770 m.

Physical Constraints on Depositional Rates

The analysis in the previous section highlighted that rapid sedimentation rates often postulated by Flood Geology models leads to unsustainably high overpressures as the dissipation of the pore water cannot keep up with the load being applied as new sediment is deposited on top. Gibson (1958) proposed the following non-dimensional time factor, T_g, which provides a measure of the balance between sedimentation rate (how quickly load is applied to the existing material) and the coefficient of consolidation, (a measure of how quickly the soil can dissipate the excess pore pressure):

$$T_g = m^2 t/c_v \quad (9)$$

T_g is a dimensionless time factor that controls the degree of overpressure build-up during deposition, m is the sedimentation rate in m/s, c_v is the coefficient of consolidation in m^2/s and t is the total time over which the sediment is deposited. In general, to prevent significant overpressure building up T_g should be less than one.

For the three scenarios tested in the previous section the values of T_g can be calculated using Equation 8. It should be noted that the sedimentation rate is usually calculated assuming a well-compacted state rather than the initial, very-loose state. For this purpose, an average porosity of 0.55 is assumed giving a total deposition height of 770 m. A constant value of $c_v = 5.10^{-8}$ m^2/s is used for all the calculations.

Scenario 1 (Flood deposit in 100 days)

m = 770 m / 100 days = 7.7 m/day
$T_g = 1.3.10^6$

Scenario 2 (post-Flood deposit in 100 years)

m = 770 m / 100 years = 7.7 m/year
$T_g = 3.7.10^3$

Scenario 3 (deposition over 9 million years)

m = 770 m / 9 million years = 85 m/Myr
$T_g = 0.04$

These results highlight why the deposition rates assumed in either Flood (Scenario 1) or post-Flood (Scenario 2) models give rise to completely unstable soil conditions with effectively no undrained shear strength. The sedimentation rates are orders of magnitude higher than the dissipation potential of the clay and, hence, it is almost completely fluidized even in the post-Flood scenario. By way of comparison with present-day field observations, it is common for submarine landslides to be prevalent in areas where the average sedimentation rate exceeds 0.1m/yr.

Implications for Dinosaur Tracks During the Flood

It is common for Flood models to include hypotheses relating to the formation of dinosaur footprints during the Flood. These hypotheses usually assume that, during the course of the Flood, dinosaurs may have walked across freshly deposited sediment as the Floodwaters rose. However, this would require that the freshly deposited sediment had sufficient strength to support the weight of a large animal.

By way of comparison, elephants produce average bearing pressures under their feet of the order of 250 kPa (Panagiotopoulou et al., 2016). In a clay, this requires an undrained shear strength of approximately 50 kPa to support this pressure. This corresponds to a moderate-strength clay. As discussed in the previous section, this degree of strength is highly unlikely to develop in silts or clays within the timeframe

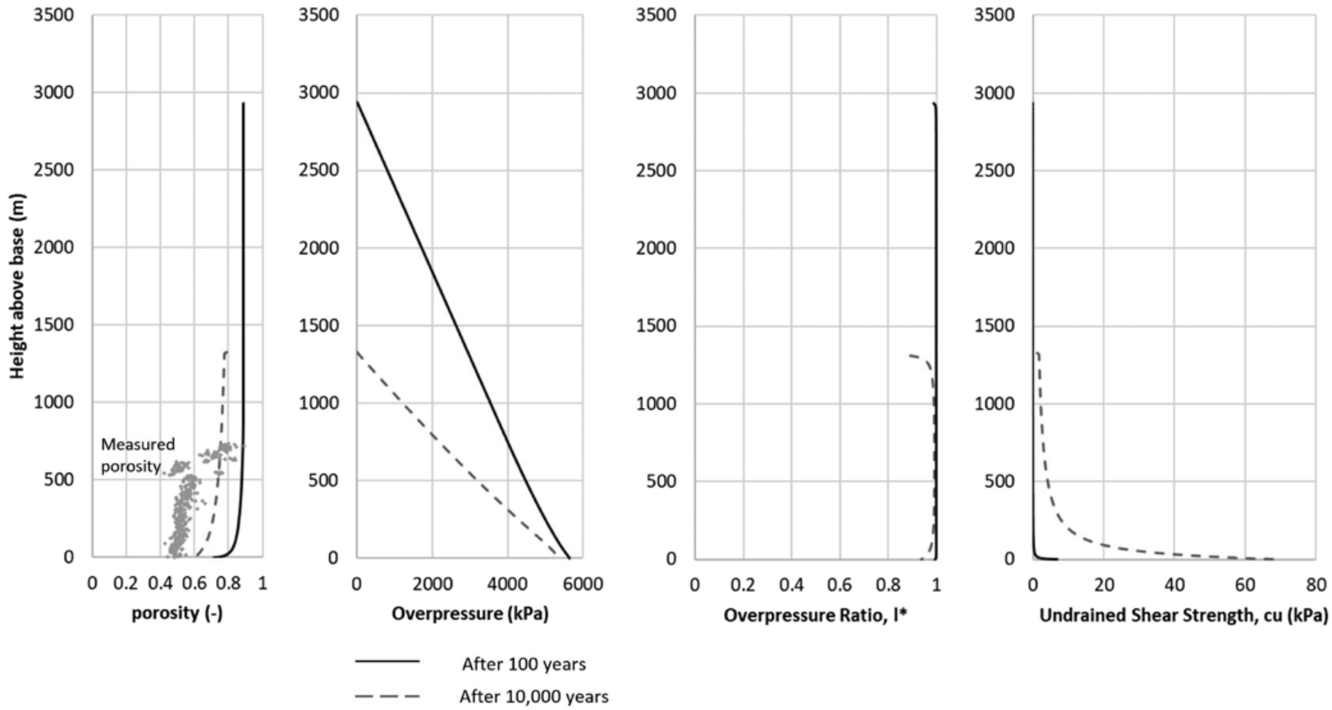

Figure 9. Scenario 2 (Post-Flood deposition over 100 years).

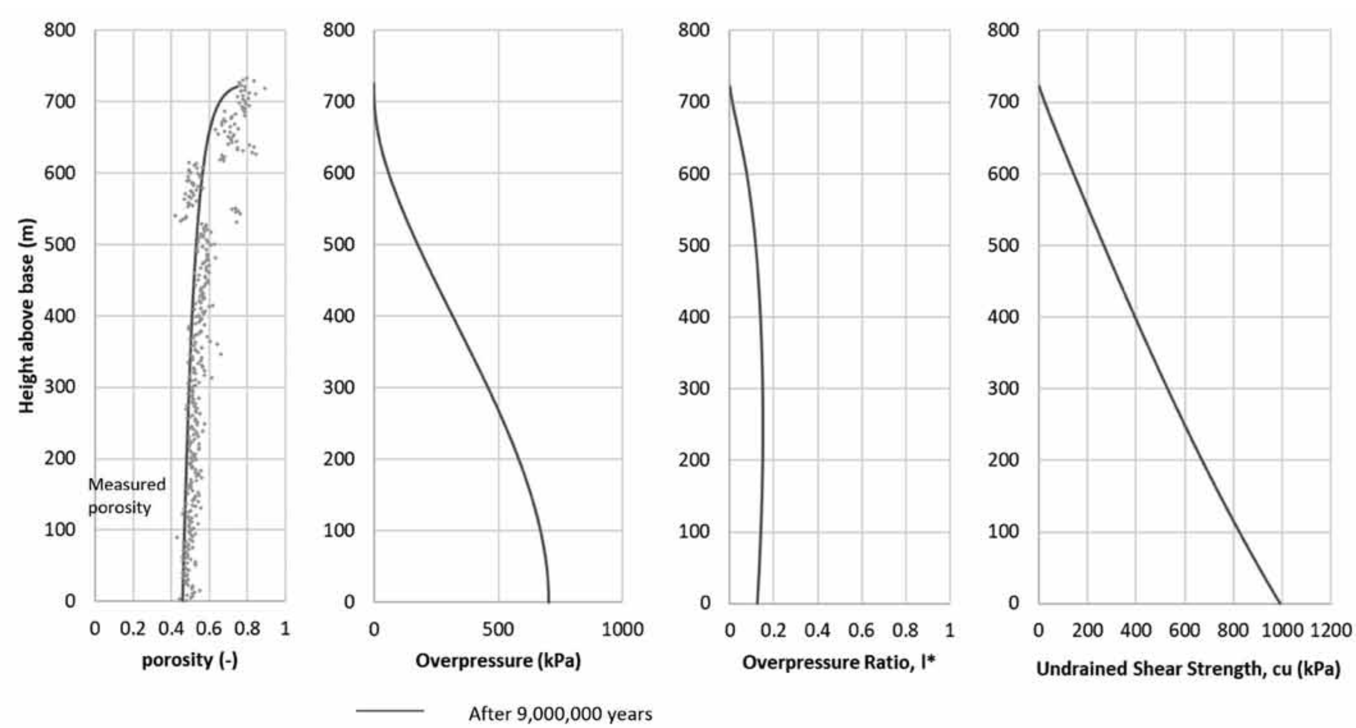

Figure 10. Scenario 3 (slow deposition over nine million years).

of hours or days and therefore it is difficult to conceive how dinosaurs could walk on freshly deposited material other than that with high sand content which would develop bearing capacity quickly.

The dinosaur track hypotheses should therefore be tested at each site against the likelihood of the freshly deposited material being able to withstand the bearing pressure of the animal. In most cases the foot area is preserved in the rock and an approximate weight of the animal is usually known allowing an estimate of the bearing pressure. Using the techniques described in this paper, the rate of gain-of-strength of the sediment can be estimated and tested against the required bearing capacity using the common formula that bearing capacity is equal to 5.14 times the undrained shear strength of the material.

Limitations and Uncertainties of the Models

Due to the extremely large range in the permeability of soil (up to six orders of magnitude difference between sand and clay), predictions made by the models presented in this paper are typically only accurate to within an order of magnitude. Also, complexities of soil profiles, presence of layers, and potential for horizontal flow may require full three-dimensional models of consolidation to be made to assess timescales. These models are commonly used in the oil and gas industry to describe the build-up and flow of hydrocarbons and are readily accessible to trained professionals. These tools would allow Flood Geology hypotheses to be tested in very complex geologies.

Conclusions

The purpose of this article was to quantitatively examine the rapid-rock formation hypotheses that are fundamental to Flood Geology models. In particular this paper has studied the timeframes required for the first phase of lithification, mechanical compaction under self-weight. The study used well-established analytical and numerical methods commonplace in geotechnical engineering.

The following general conclusions can be made:

- There is a very large change in volume required to consolidate mud to stiff clay (approximately 4 to 1) or to claystone (approximately 10 to 1). This would mean that for every 100 m of claystone created, 1000 m of freshly deposited clay is needed.
- The primary constraint on the rate of consolidation is the permeability. The maximum velocity that water can be expelled from a soil is equal to the hydraulic conductivity, *K*, which for clays is in the order of 10^{-11} to 10^{-9} m/s (0.3 mm/year to 30 mm/year). This highlights the extremely slow nature of fluid flow in clay.
- Basic soil mechanics shows that consolidation times for1000 m-thick clay layers are in the order of millions of years.
- If deposition rates in clay exceed approximately 0.1 m/year, a high degree of overpressure will form leading to geotechnical instability such as submarine landslides or even complete fluidization of the soil. The rates proposed in both Flood models (average sedimentation rate of 10 m/day) and post-Flood models (average sedimentation rate of 10 m/year) are between a hundred to one million times higher than this physical limit.

Even allowing for uncertainty in the geotechnical parameters and the assumptions regarding one-dimensional vertical flow (i.e., no horizontal flow), it is difficult to see how the consolidation of clay as understood by present-day geotechnical engineering formulations can accommodate the rapid deposition and consolidation of clay within young-Earth timeframes, whether that be during the Flood or post-Flood. In order to provide credible Flood Geology models, it will therefore be necessary to propose mechanisms that can account for accelerating the consolidation phase by many orders of magnitude compared to standard soil mechanics.

However, as highlighted in this paper, there are physical limits to the rate of consolidation that cannot be exceeded without fluidizing the soil and losing all of its strength. Even clay layers that are sandwiched between sand layers cannot be loaded at rates beyond those presented in this paper without creating excessive overpressure and weakening the clay. This would ultimately result in the overlying sand layers punching through the weak clay.

It is therefore recommended that initial hypotheses are tested against two basic rules of thumb to confirm feasibility:

a) Time (in seconds) assumed for rock formation $< H^2/c_v$, where H(m) is the thickness of the layer in question and c_v (m^2/s) is the coefficient of consolidation. In the absence of any specific site data, the values presented for c_v in Tables II and III can be used.
b) The maximum sedimentation rate, m (m/s) $< \sqrt{C_v/t}$, where t (s) is the duration of the sedimentation process. This would ensure that excess pore pressures remain below limits that could result in large-scale geotechnical instabilities.

The above formulae are applicable for all fine-grained material where consolidation is likely to be problematic including silts, clays, and oozes. It is unlikely that sand or coarser-grained materials will experience such issues.

References

CRSQ: Creation Research Society Quarterly

Arthur, M.A., S.P. Srivastava, B. Clement, et al. 1985. Ocean Drilling Program Leg 105, Baffin Bay and Labrador Sea. Preliminary Report, Shipboard Scientific Party.

Baumgardner, J. 2018. Understanding how

the Flood sediment record was formed: The role of large tsunamis. In *Proceedings of the Eighth International Conference on Creationism*, ed. J.H. Whitmore, pp. 287–305. Creation Science Fellowship, Pittsburgh, PA.

Bjorlykke, K. 1998. Clay mineral diagenesis in sedimentary basins—A key to the prediction of rock properties, examples from the North Sea Basin. *Clay Minerals* 33(1):15–34.

Clarey, T.L., and D.J. Werner. 2019. South Caspian Basin supports a late Cenozoic Flood boundary. *Journal of Creation* 33(3):8–11.

Dadey, K.A., and A.J. Silva. 1989. Consolidation and strength of Pliocene-Pleistocene sediments from Site 646 and 647, ODP Leg 105, Chapter 41. *Proceedings of Ocean Drilling Program*, Scientific Results, Vol. 105.

Dunn, S.L., P.L. Vun, A.H. Chan, and J.S. Damgaard. 2006. Numerical modeling of wave-induced liquefaction around pipelines. *Journal of Waterway Port Coastal and Ocean Engineering-ASCE*, 132:276–288.

Flemings, P.B., John, C., and Berhrmann, J., 2012. Expedition 308 synthesis: overpressure, consolidation, and slope stability on the continental slope of the Gulf of Mexico. Proc. IODP, 308. Integrated Ocean Drilling Program Management International, Inc., College Station, TX.

Freeze, R.A., and J.A. Cherry. 1979. *Groundwater*. Prentice-Hall, Inc, Englewood Cliffs, NJ, 604 pages.

Gibson, R.E. 1958. The progress of consolidation in a clay layer increasing in thickness with time. *Geotechnique* 8:171–182.

Hillier, S. 1995. Erosion, sedimentation, and sedimentary origin of clays. In Velde, B. (editor). Origin and Mineralogy of Clays. Springer-Verlag, New York, NY, pp. 162–219.

Klevberg, P., and Oard, M.J. 2023. Lithification of Clastic Sediments—Part 1: Significance, Processes, and Modeling. *CRSQ* 60(1):11–28.

Oard, M.J. 2007. Defining the Flood/post-Flood boundary in sedimentary rocks. *Journal of Creation* 21(1):98–110.

Orozova-Bekkevold, I., and Petersen, T.G. 2021, Numerical forward modeling of the overpressure build-up in the Cenozoic section of the Central Graben in the North Sea. *Journal of Petroleum Exploration and Production* 11:1621–1642.

Panagiotopoulou, O., et al. 2016. Foot pressure distributions during walking in African elephants (*Loxodonta africana*). *Royal Society Open Science* 3(10).

Sawyer, D.E., P. Flemings, B. Dugan, J.T. Germaine.2009. Retrogressive failures recorded in mass transport deposits in the Ursa Basin, Northern Gulf of Mexico. *Journal Geophysical Research* [Solid Earth] 114(B10):B10102.

Shridharan, A., and H.B. Nagaraj. 2004. Coefficient of consolidation and its correlation with index properties of remolded soils. *Geotechnical Testing Journal* 27(5); DOI:10.1520/GTJ10784.

Soulsby, R.L., A.J. Manning, J. Spearman, and R.J.S. Whitehouse. 2013. Settling velocity and mass settling flux of flocculated estuarine sediments. *Marine Geology* 339:1–12.

Srivastava, S., M.A. Arthur, et al. 1987. Proc. IODP, 105. Integrated Ocean Drilling Program Management International, Inc., College Station, TX.

Tergazhi K. 1922. Der grundbruch an stauwerken and seine verhiltung. *Die Wasserkraft* 17.

Van Rijn, L.C. 2018. *Consolidation of Mud-Sand Mixtures*. LVR-Sediment Consultancy, Blokzijl, The Netherlands; www.leovanrijn-sediment.com.

Vousdoukas, M., A.F. Velegrakis, and T. Plomaritis. 2007. Beachrock occurrence, characteristics, formation mechanisms, and impacts. *Earth-Science Reviews* 85(1–2):23–46.

Winterwerp, J.C. 1999. On the dynamics of high-concentrated mud suspensions, Ph.D. diss., Delft University of Technology (TU Delft), Delft, Netherlands.