Lessons from a mixed deterministic stochastic model of periglacial gnamma development.

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Abstract

A theory of periglacial gnamma development in Chile, Minnesota, and Portugal claims that the maximum depth of gnammas (h) divided by the maximum depth of water which can be held by the gnammas (u) can be used to identify numerous periods of gnamma initiation on the rock surfaces. Surprisingly, h and u are positively correlated in the real data but must be negatively correlated in the theory. A deterministic computer model shows that if the rate of deepening of the gnamma is more rapid than in the spillway connected to the gnamma, h and u must be positively correlated as in the data. The simulations also show that it is more likely that all the gnammas on a surface develop at about the same time, a few centuries after the surface is exposed, and after that, few if any new gnammas are formed. The models also explain why the frequency distributions of h/u are asymmetric and skewed toward the small size gnammas. In the simulations, and on the outcrop, h/u approaches a steady state after thousands of years that is a function of the average rate of weathering of rock, not the initiation of new sets of gnammas.

Meta-Introduction

James Hutton taught Sir Charles Lyell that “The present is the key to the past” but some present activities are too complex for the human mind to comprehend and so we use computer models to understand the present and reconstruct the past. This has been so in meteorology and oceanography for many decades, however even seemingly simple field studies might benefit from the assistance of computer modeling early in the study, to direct the field studies. Consider the gnamma, a simple weathering pit on a horizontal surface that presumably forms by accident, and then deepens because it stores water that causes more rapid weathering in the pit than on the surrounding drier but otherwise identical rock. The following study shows that the gnamma is just a little too complex for the human mind to predict its behavior, and that some gnamma field workers would have benefited from a little computer modeling to guide their thinking and their data gathering.

Introduction

A gnamma (English) or pilancone (Spanish) is a concavity caused by weathering and erosion of the surface of a rock. "Gnamma" (pronounced "namma") is an English word derived from the Australian Aborigine Nyungar language. Gnamma vary from a few mm (Achyuthan et al. 2010) to tens of meters deep and wide. They are most commonly reported on granitic surfaces (Twidale and Corbin, 1963) but they are also common in sandstone (Tarkington, 2005) and they are less commonly found on gneiss (Klein, et al., 1997), basalt (Dorn, 1995), basic charnockite (Achyuthan et al. 2010), limestone (Gutierrez, 1979) and other rocks. Gnammas are defined as pans if they are horizontal disks and pits if they are hemispherical (Twidale and Corbin, 1963). Very few gnammas are deeper than they are wide.

Gnammas are weathering pits on near horizontal surfaces, unlike tafoni, that are weathering pits on steep surfaces. It is assumed that gnammas weather faster than the unpitted surface around them because gnammas hold water and weathering is mostly due to hydrolysis, salt precipitation, frost action, and other processes involving water. However, the causes of gnammas and tafoni are still not well known and there may be multiple causes (Mustoe, 2010). Recent cosmogenic studies have shown that larger gnammas are found on older surfaces (Hall and Phillips, 2006), and the gnammas increase in size following a sigmoidal equation that starts slowly and becomes rapid, then slows to a much slower rate of growth as do some tafoni (Norwick and Dexter, 2002). Gnammas are found in all climatic zones including tropical (Achyuthan et al. 2010), arid (Twidale and Bourne, 1975), temperate (Smith, 1941), Mediterranean (Domínguez-Villar, 2008), and periglacial climates (Matthes 1930).

Figure 1. Gnammas, one with stone in middle, with a spillway and channel flowing into the right side of the gnamma and out the left side of the gnamma, Tamil Nadu, southeast India.

Many different theories have been advanced to explain why some spots on a rock surface develop a gnamma and a contiguous spot does not. Sometimes, petrological differences, such as xenoliths, make one spot weather more rapidly (Kastning, 1976). The Glossary of Geology (Bates and Jackson, 2005) states that gnammas are usually found at the intersections of joints, which is sometimes true (Twidale and Bourne, 1977; Twidale and Sved, 1978; Vidal Romani and Murguía, 1984), but a review of the literature and extensive field experience suggests this is often not the case. In fact, there are places where gnammas and tafoni forms in massive granite whereas nearby well jointed and faulted granite does not have gnammas and tafoni (Horishi, 2001). Twidale also believes that gnammas are initiated by subsoil chemical processes and then the surface is stripped and exposed to surficial weathering (Twidale and Bourne, 1975). In some cases, lichen and moss crusts form a gnamma where the crust is disturbed and causes a large flake to detach from the surface (Souza-Egipsy et al. 2004).

Gnamma and tafoni may form on rock surfaces due to case hardening. Tafoni with visors are often assumed to be formed where a strong weathering patina has finally broken and exposed softer, weathered rock which then weathers and erodes rapidly to make a tafone or gnamma that has a larger interior diameter than the aperture. In Hawaii, gnammas form on basalt when a protective silica glaze is broken and the weaker underlying rock is eroded (Dorn 1995).

However, the most common theory is that a near horizontal surface is exposed to weathering with small depressions that fill with water, and therefore weather more rapidly than the rest of the surface coefficients (Domínguez-Villar, 2006; Domínguez-Villar and Jennings, 2008; Domínguez-Villar et al., 2009). Miarolitic cavities may be the initiating depressions. Granite with more miarolitic cavities seem to have more tafoni and gnammas around the work in Finland (Kejonen et al., 1988), and Korea (Kim et al., 2010).

Gnamma are often drained by a rock cut channel called a "rill" or "solution flute" or "channel" (English), "rillenkarren" (German), "exutorio" (Spanish), or "lapiés" (French Swiss). The place at the side of the gnamma where it meets a channel is called the spillway. If this spillway is deeper than the gnamma, the gnamma will no longer hold water, and the two features together are called an "armchair" (English) or "sillón" (Spanish). Some geomorphologists insist that a gnamma must be able to hold water (Domínguez-Villar et al. 2009).

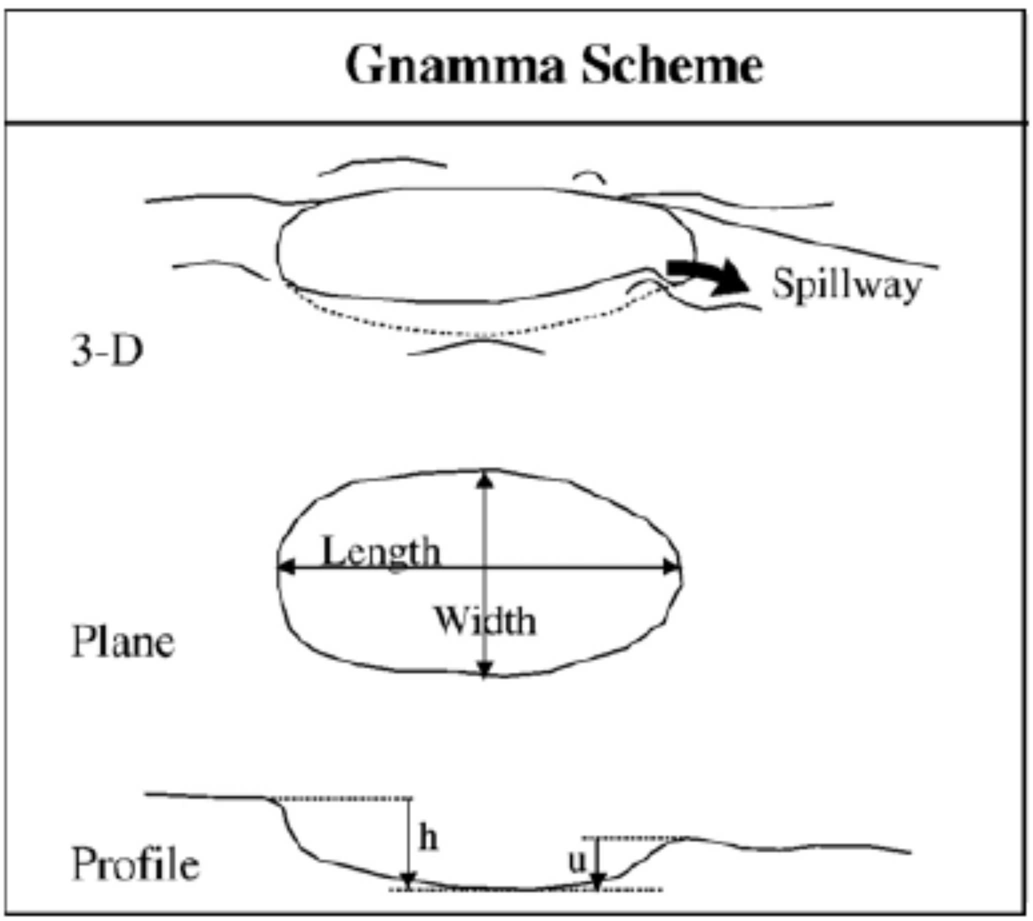

Figure 2. Diagram defining how to measure gnammas (Domínguez-Villar, 2006, p. 140; Domínguez-Villar and Jennings, 2008, p. 169). The maximum depth of the gnamma is h, and u is the maximum depth of water that the gnamma can hold. The depth of the spillway plus u are equal to h. The ratio h/u, the "depth ratio" is always ≥ 1 and is called **δ**.

Studies of Periglacial Gnammas of Chile, Minnesota, Portugal and Spain

Between 2006 and 2009, a series of papers appeared in which an interesting hypothesis was proposed and tested using field studies of glaciated areas in Patagonia, Chile (Domínguez-Villar, 2006), Minnesota (Domínguez-Villar and Jennings, 2008) and the mountains of Portugal (Domínguez-Villar et al., 2009). Instead of using the depth, length and width of the gnammas as is usual in studies of gnammas and tafoni (de Uña Alvarez, 1998; Hall and Phillips, 2006), Domínguez-Villar and his associates concentrated their interest on the depth ratio. In each case, they showed that h and u are correlated very well to moderately (Figure 3). This is consistant with two earlier studies of gnammas from Galicia, Spain where strong positive correlations were found between h and u (de Uña Alvarez, 1998).

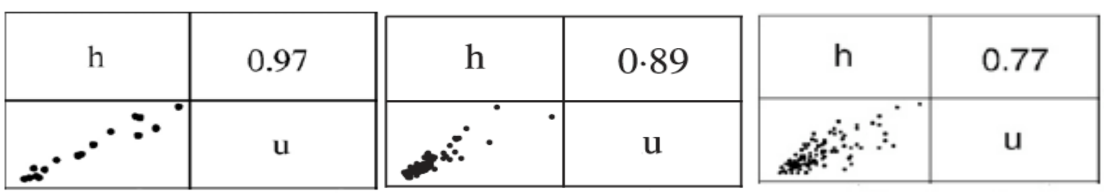

Figure 3. Relative correlation between h and u in cm of gnammas in recently deglaciated areas of Chile, Minnesota, and Portugal. These graphs were presented without scales in the original papers. The numbers in the boxes above u are the correlation coefficients (Domínguez-Villar, 2006, p. 142; Domínguez-Villar and Jennings, 2008, p. 171; Domínguez-Villar et al., 2009, p. 224).

In Chile (Figure 3, left side) and Minnesota (Figure 3, middle) the maximum depth (h) and the depth of water (u) are well correlated. In Portugal, h and u are not statistically correlated (Figure 3, right side) but the pattern on the graphs of h versus u suggests positive correlation and is certainly incompatible with a negative correlation. "Thus the depth ratio has been used to characterize the gnammas for discrete locations" which is said to be "a powerful tool to understand these morphologies . . . " (Domínguez-Villar, 2006, p. 137).

The mental model of Domínguez-Villar is based on an idealized scenario of gnamma development. The initial subhorizontal surface is created fairly rapidly, usually by deglaciation. Small areas, a few mm lower than the rest of the surface, hold snow, ice and water longer than the adjacent surface, and weather more rapidly. Most of the weathering is vertical, so the incipient gnamma deepens but does not spread sideways very much. During some times of the year, the gnamma overflows with water that eventually causes a spillway and channel. For some centuries, the gnamma deepens faster than the spillway. Then, for no reason that is stated, the channel begins to deepen more rapidly than the gnamma and eventually the top of the channel is below the elevation of the bottom of the gnamma so that there is no longer a pool of ice or water in the gnamma which is continuously drained, and the form has become an armchair. The authors of these papers say that an armchair is a "nonweathering depression" and they did not study them. They also rejected any gnamma that has a u value < 15 mm because it is "too mature" (Domínguez-Villar, 2006, p. 140).

In this scenario (a mental model), the gnamma depth (h) is increasing as the depth of the water in the gnamma (u) is decreasing, so we expect h and u to be negatively correlated, not positively correlated. But the data from Chile and Minnesota have statistically significant positive correlations between h and u, and even the right hand graph from Portugal (Figure 3) which is not statistically significant, is clearly not showing a negative correlation.

The theory is clear enough to make a numerical computer model in the STELLA language that reproduces the scenario of their theory.

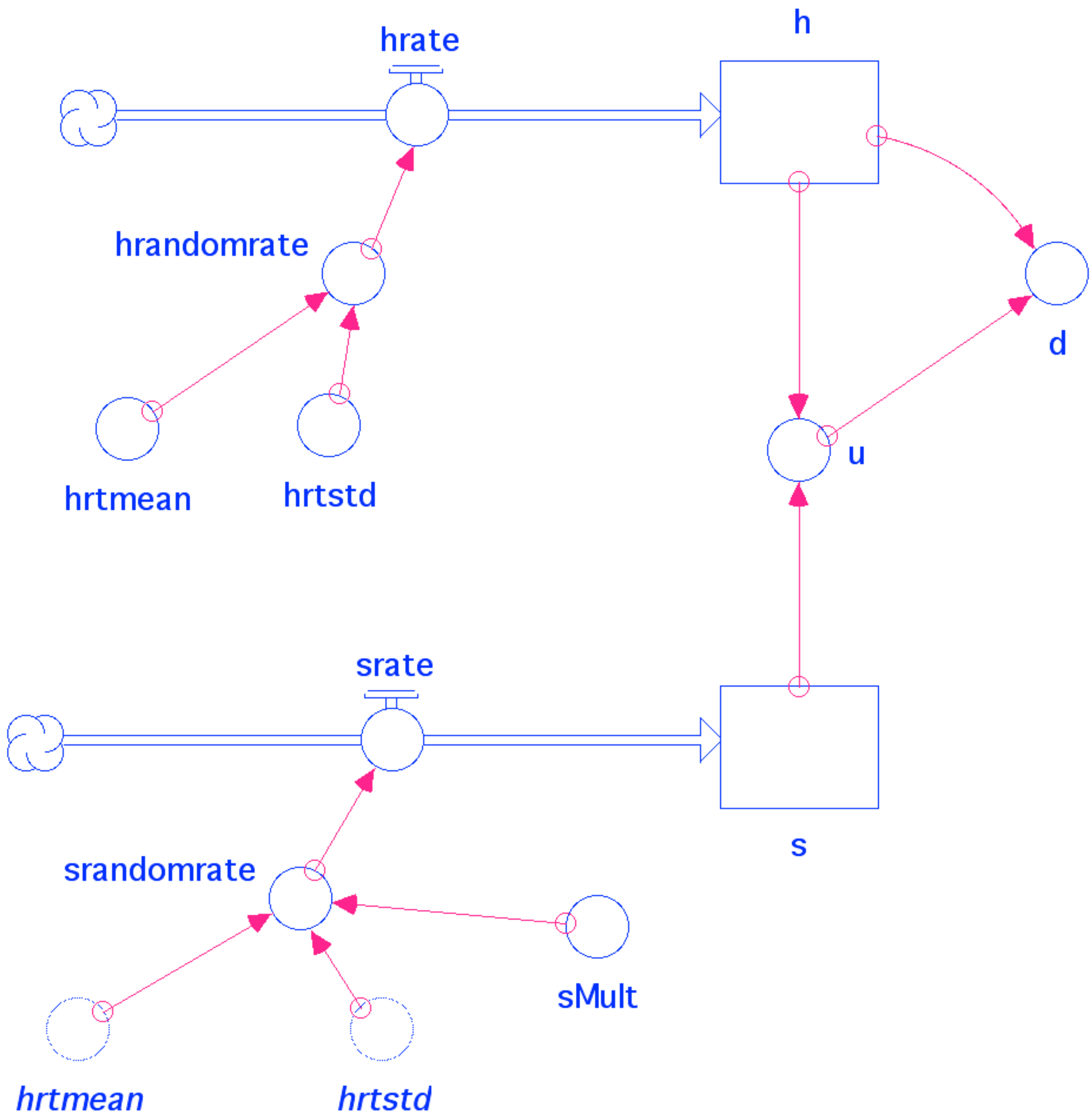

Figure 4 System Dynamic flow diagram of the model history of gnamma and spillway formation and development.

h	maximum depth of the gnamma
s	depth of the spillway of the gnamma
u	depth of water in the gnamma = h-s
d	ratio of h/u
hrate	rate of deepening of the gnamma
srate	rate of deepening of the spillway
hrtmean	mean rate of gnamma deepening

hrtsdt	standard deviation of gnamma deepening
sMult	multiplier that makes the spillway weather more rapidly positive number greater than 1
hrandomrate	preliminary computed rate of gnamma deepening
srandomrate	preliminary computed rate of spillway deepening

The model is largely deterministic, that is it has a clear set of causal relationships. However, this model also has stochastic processes, random events by which the gnamma and the spillway deepen (Figure 5) with a Gaussian (bell shaped curve of) probability distributions of thousands of tiny erosion events. This is similar to the real gnamma in the studies (Domínguez-Villar, 2006; Domínguez-Villar and Jennings, 2008; Domínguez-Villar et al., 2009).

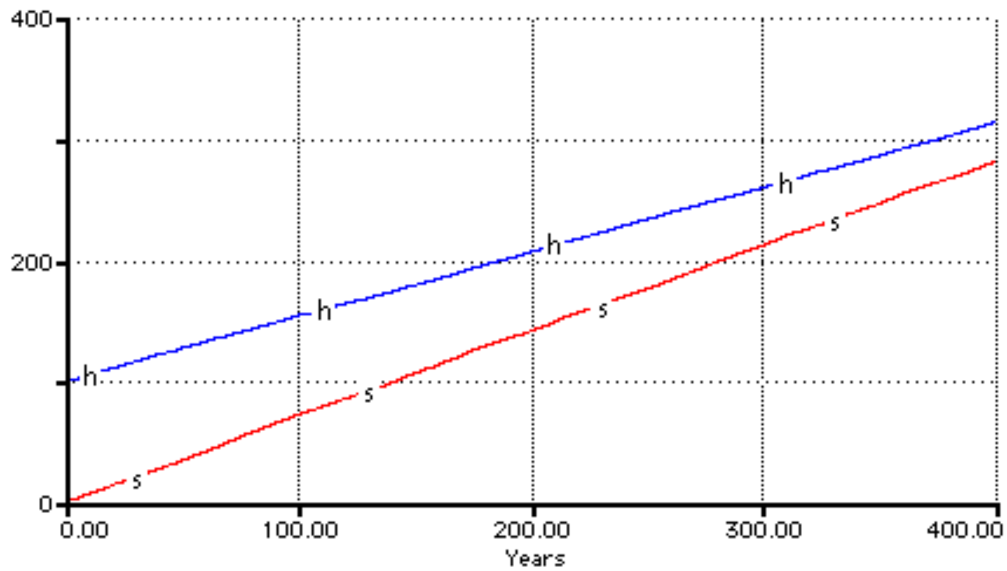

Figure 5. Model 1 computations of maximum depth in mm of the gnamma (h) in mm and the spillway (s) increase with time in years. The spillway starts out at zero but increases more rapidly so that eventually the spillway drains the gnamma.

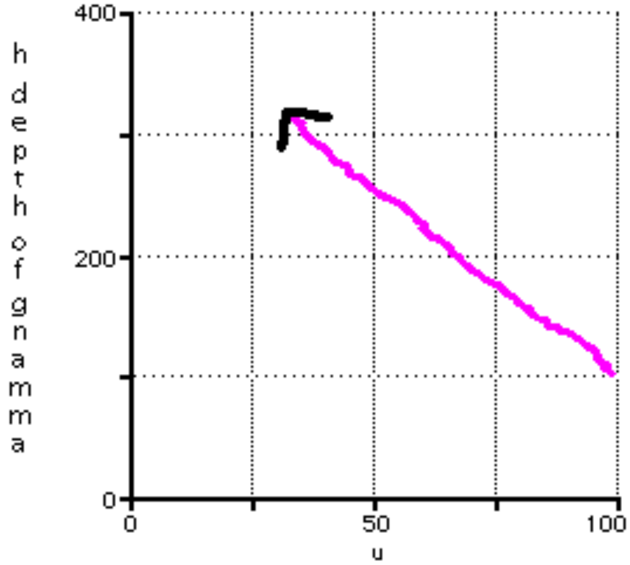

Figure 6. Model 1 shows the maximum depth in mm of the gnamma (h) versus the maximum depth of water that the gnamma can hold (u) are strongly negatively correlated as demanded by the theory of Domínguez-Villar, 2006.

Notice that h and u are clearly negatively correlated (Figure 6). The simulation begins on the lower right hand side and drives toward the upper left, symbolized by the arrow head. The real data (Figure 5) is clearly completely unlike this graph, therefore the theory must be wrong. There is no change in the initial states or most of the parameters that can make the model like the real system. We must explain the real data with some better theory in which the maximum depth of the pits and the depth of water in the pits both increase together (Figure 5).

A New Scenario To Correctly Explain the Field Data

A scenario that can account for the data that is presented in Domínguez-Villar, 2006; Domínguez-Villar and Jennings, 2008 and Domínguez-Villar et al., 2009, must start with a near planar surface with tiny random depressions. The depressions are so small that almost all rainwater flows away at once. However, the deeper these initial depressions are, the longer water will stay on the surface and the more rapidly the stone will weather. The spillways for these tiny depressions are somewhat drier than the depressions, but they still weather more rapidly than the drier interfluves (the little ridges between channels) which are only wet when it is raining. The STELLA computer model for this history is the same as figure 4 except sMult is a positive number between 1 and zero. This is scenario 2.

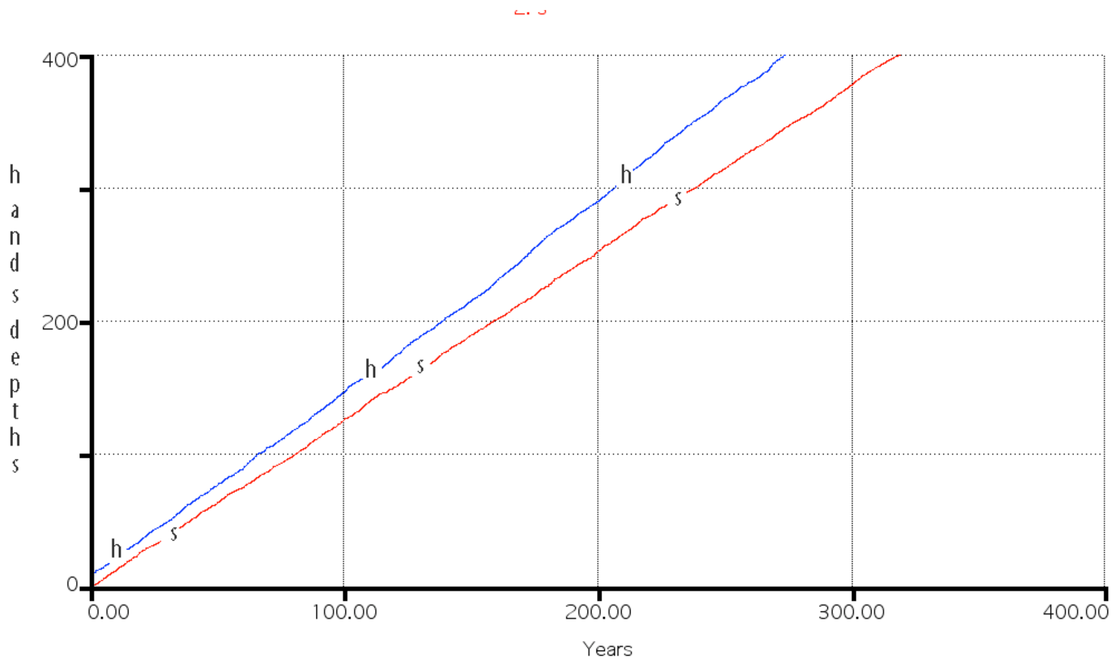

Figure 7. Simulation scenario 2, the maximum depth h and the spillway depth s of the gnamma increase. The vertical distance between h and s at any time is u, the maximum depth of water in the gnamma.

The gnamma deepens faster than the spillway because it is wetter more of the time and has more chemical degradation of the minerals by hydrolysis and more frost cycles (Figure 7). This makes more sense than scenario 1 which could not explain why the relative weathering rates changed for the gnamma and its spillway.

As the depth of the gnamma and its spillway increase, the lip which holds in the water becomes higher (u) and more water is contained in the gnamma (Figure 8).

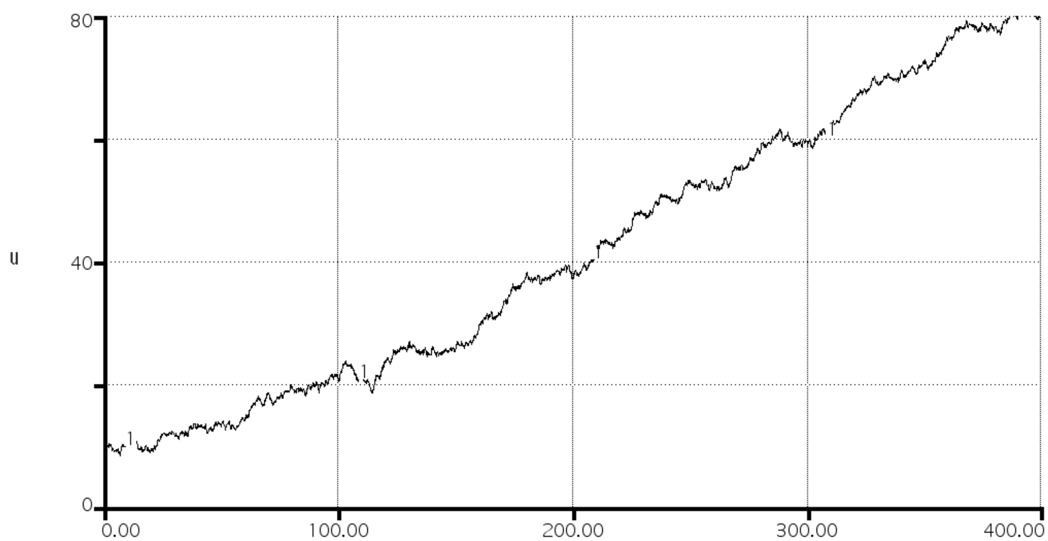

Figure 8. The depth of the water in the gnamma, u in mm, increases with time in years.

In Chile, Minnesota and Portugal, periglacial surfaces have gnamma with positively correlated maximum depth h and water depth u (c.f. Figure 3 above, and Domínguez-Villar, 2006; Domínguez-Villar and Jennings, 2008 and Domínguez-Villar et al., 2009). This strongly disproves scenario 1 and verifies scenario 2 of gnamma development (c.f. Figure 9).

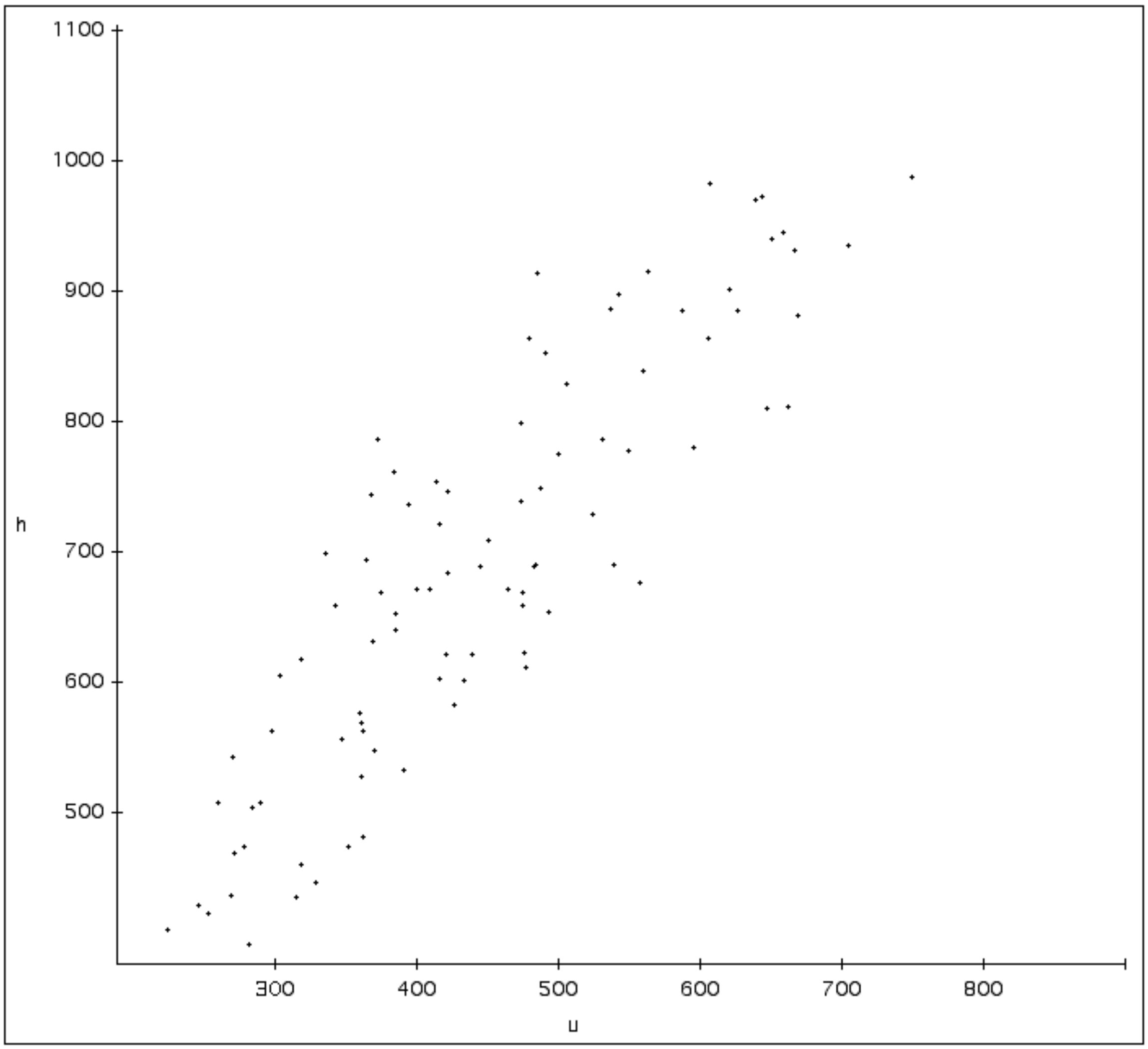

Figure 9. The depth of 100 gnammas (h in mm), versus the manimum depth of the water in the same 100 gnammas (u in mm) from 100 simulations with model 2. Both h and u increase and are positively correlated as in the field data.

The d ratios from Chile, Minnesota and Portugal was not presented as a timeshape (c.f. Figure 10) but we are told that the d ratio seems to be stabile in certain areas (Domínguez-Villar, 2006; Domínguez-Villar and Jennings, 2008 and

Domínguez-Villar et al., 2009). The model shows us that this stability is not really a matter of geology or climate, because those factors are not addressed in the models. The stability of the d ratio in the models is a function of the geometry of any gnamma, and the mathematical relationships in the models (Forrester, 1968; Randers, 1980). It would be easy to generate this diagram from the field work even if the ages of the surfaces are not precisely known because Domínguez-Villar and his colleagues believe that new gnammas are initiated continuously so it should have occurred to them to try to create this type of graph.

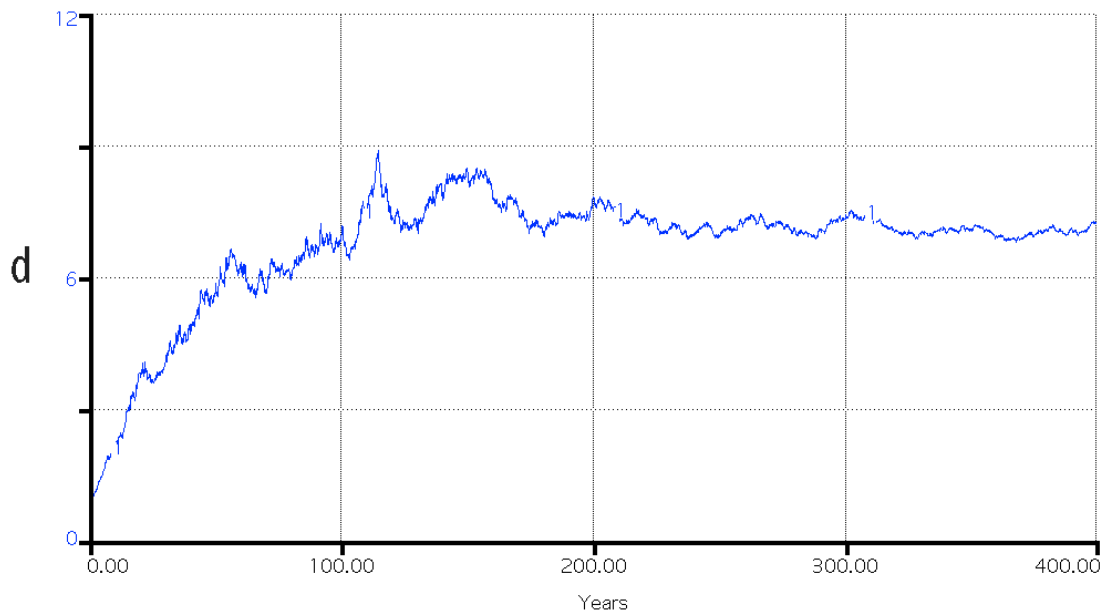

Figure 10. The simulated time shape of the d ratio of a single gnamma shows that the d ratio has a steady state in the model, in this case after 200 years.

It would have been easy for Domínguez-Villar et al. to create a diagram of the d ratio as a function of h (Figure 11) but it does not seem to have occurred to them. This is one of the advantages of using computer modeling, especially BEFORE field studies are done. It is not too late. I hope Domínguez-Villar will construct d ratio versus h diagrams for all his interesting areas and report them to us. Models often give us insights that suggest field work we should do. The numerical stability explains the natural occurrence of sets of gnammas with similar d ratios. The Domínguez-Villar et al. have found sets of gnammas with similar d ratios and interpreted them as the signs of episodes during which new sets of gnammas have been initiated (Domínguez-Villar, 2006, p. 144; Domínguez-Villar and Jennings, 2008, p. 171; and Domínguez-Villar et al., 2009, p. 224). A series of experiments with model 2 of scenario 2 suggests a new interpretation (Figure 11).

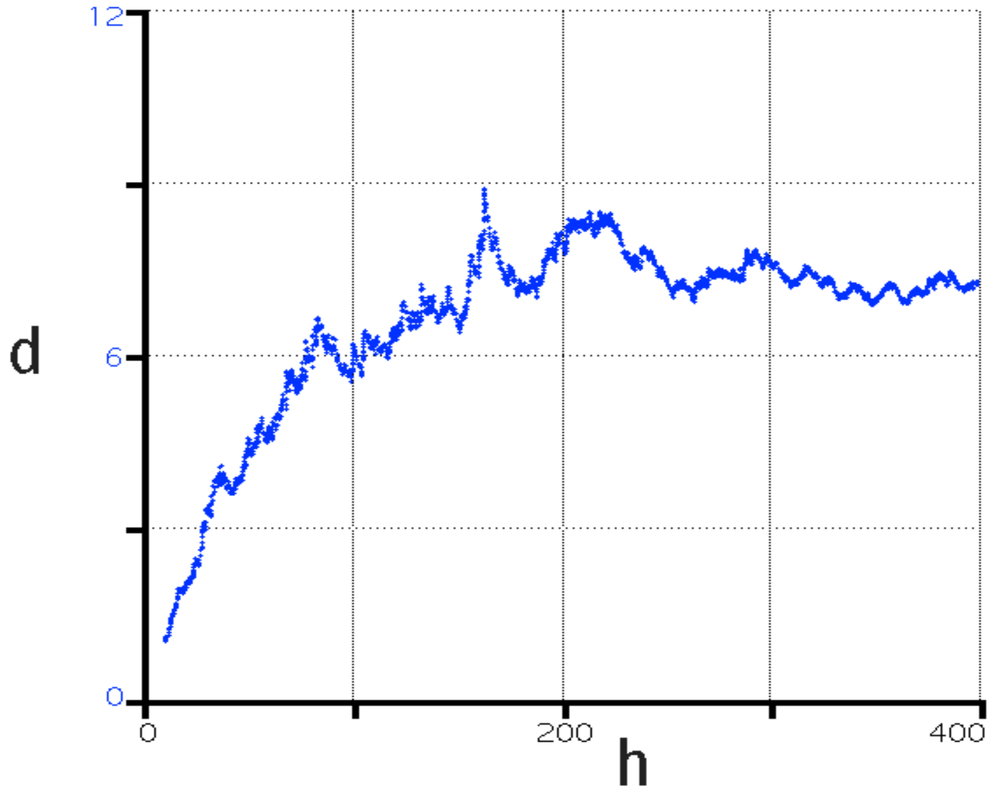

Figure 11. The d ratio (h/u) of a single gnamma stabilizes in the model after the maximum depth of the gnamma reached 200 mm.

In Figure 12, the randomizationwas turned off, to make the experiment clearer. The model was run six times, each time with a different average rate of weathering: 1000, 100, 10, 1, 0.1, and 0.01 mm/year. Admittedly, 1000 mm/year is unrealistic, but we can use this set of simulations to see that the steady state of the d ratio declines as the average rate of weathering declines. Note that the slowly weathering simulations do not reach a steady state within the 1200 years of the simulation, but they are very slowly increasing. Thus, model 2 explains a characteristic of the field data, the stability of the d ratios, in an unexpected way, which strongly increases our confidence in the model.

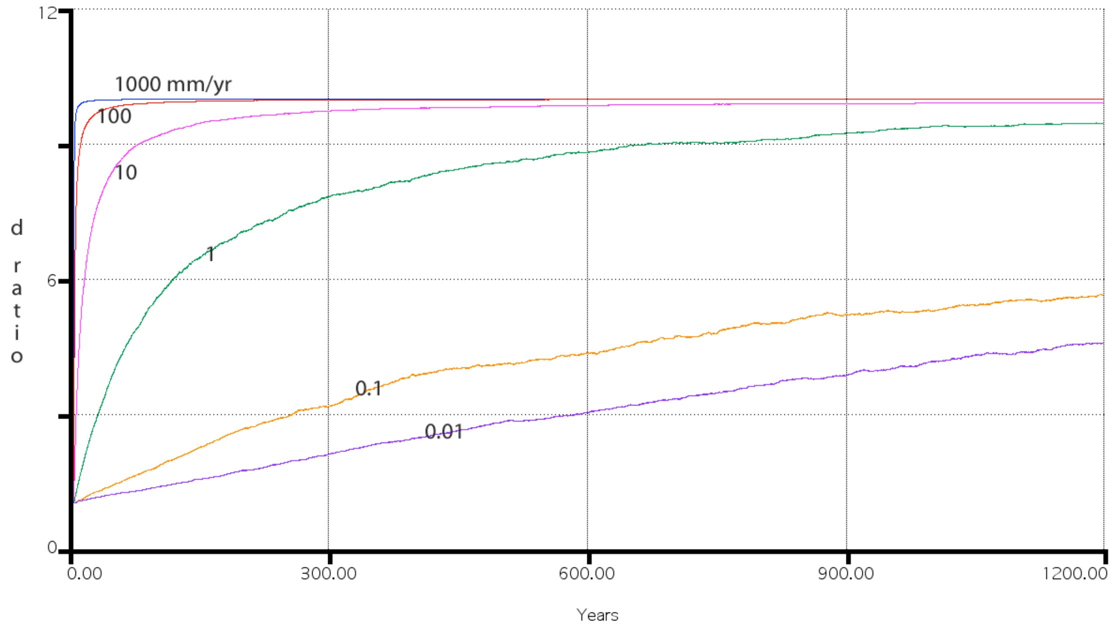

Figure 12. Time shapes of the d ratio as a function of 5 orders of different rates of weathering over 1200 years without the stochastic elements.

The sMult (Figure 4) causes the rate of weathering and erosion of the spillway to be slower than the rate of weathering and erosion of the gnamma. sMult can vary from slightly less than 1 to zero. When sMult is near 1 (0.9 in Figure 13), the spillway become a larger number just a little more slowly than the gnamma (Figure 7) so u (h-s) is a small number (Figure 7). By definition we divide h by u to get d, so d is inverse to u, so the d ratio is a larger number when sMult is larger and u is smaller (Figure 13). When sMult is smaller (0.4), the spillway lowers much more slowly than the gnamma, u (h-s) is much larger. The d ratio is inverse to u, so if sMult is smaller, u is larger, and the steady state value of d is smaller (Figure 13).

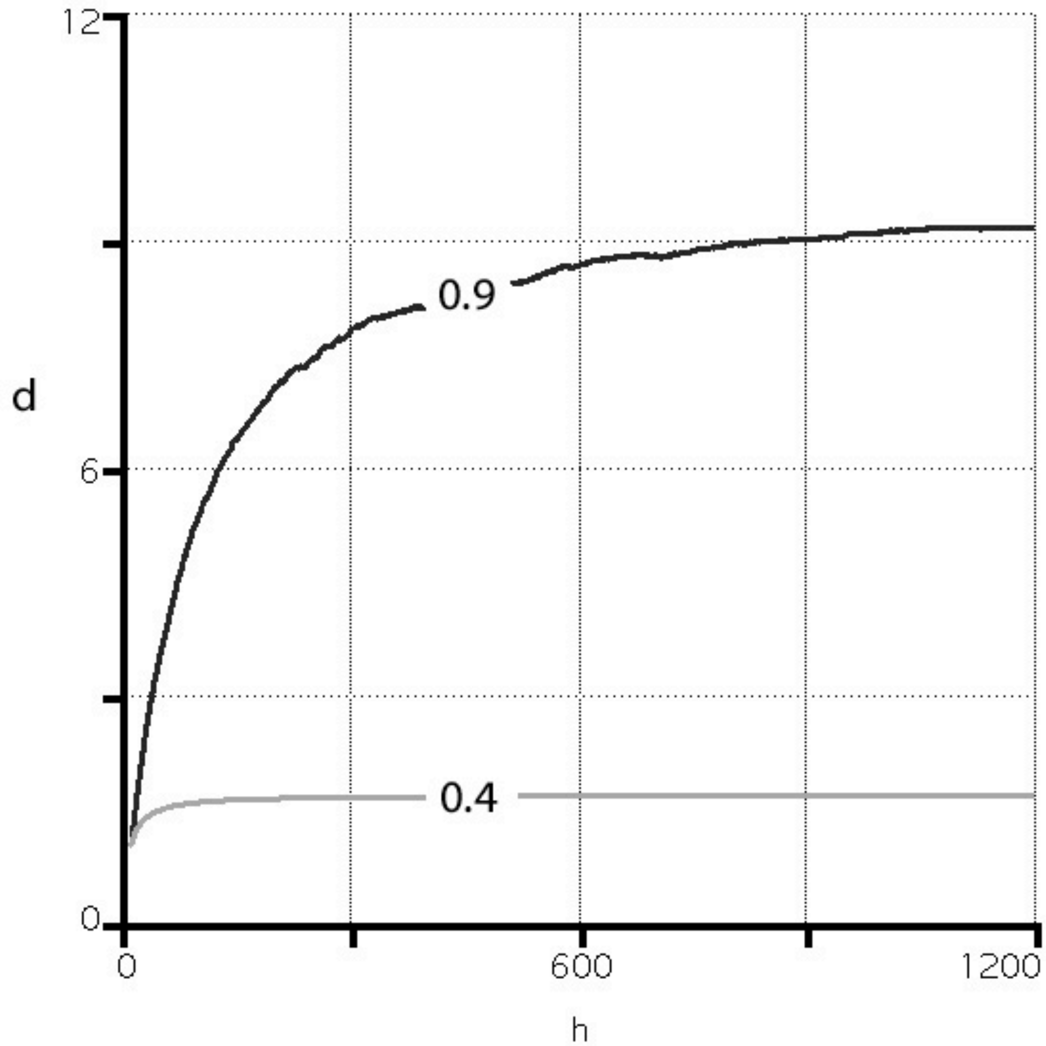

Figure 13. The d ratio stabilizes at 9 units when the rate of spillway weathering is 0.9 the rate of gnamma deepening. The d ratio stabilizes at 1.5 when the rate of spillway weathering is 0.4 the rate of gnamma deepening.

Are There Multiple Stages of Gnamma Initiation?

The peculiar statistics of tafoni and gnammas have caused Domínguez-Villar and his predecessors to misunderstand and over interpret their own data. The new computer model provided here explains (unexpectedly) the distribution of their data, and shows a simpler explanation for the variety of d values that they have discovered.

Domínguez-Villar wrote: "Usually, the gnammas measured at a station do not follow a Gaussian distribution. Rather, these gnammas have an asymmetrical density curve with a pronounced maximum close to the lowest values and a long tail toward higher depth ratios." (Domínguez-Villar, 2006, p. 143)

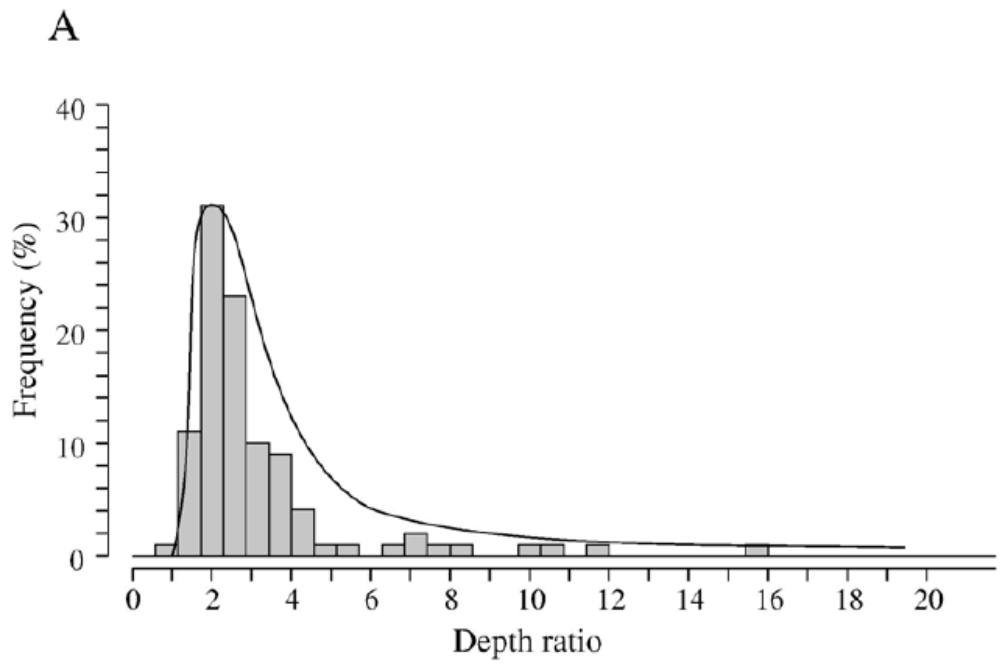

Figure 14. The frequency distribution of d ratios from El Yelmo, Spain (Domínguez-Villar, 2006, p. 144).

However, gnammas from Chile, which is on the youngest surface studied in this series of papers, have a Gaussian distribution. All the other sites follow his earlier statement as in Figure 14 (Domínguez-Villar and Jennings, 2008, p. 171; and Domínguez-Villar et al., 2009, p. 222).

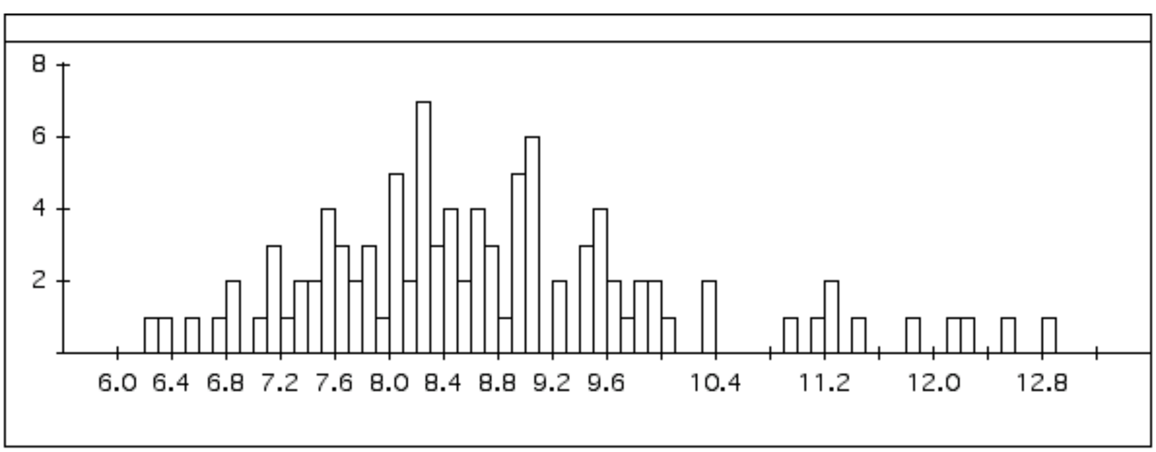

Figure 15. An artificial frequency distribution of 100 d ratios from model 2.

When a model produces a behavior that is similar to nature and which is unexpected, it enhances the believability greatly. Model 2 starts with tiny Gaussian distributed random weathering and erosion but the system produces a frequency distribution of d ratios that are skewed toward the left (Figure 15) with a few, very large d ratios on the right hand side just like the real data (Figure 14). This gives us even more confidence in scenario 2 and its modeling.

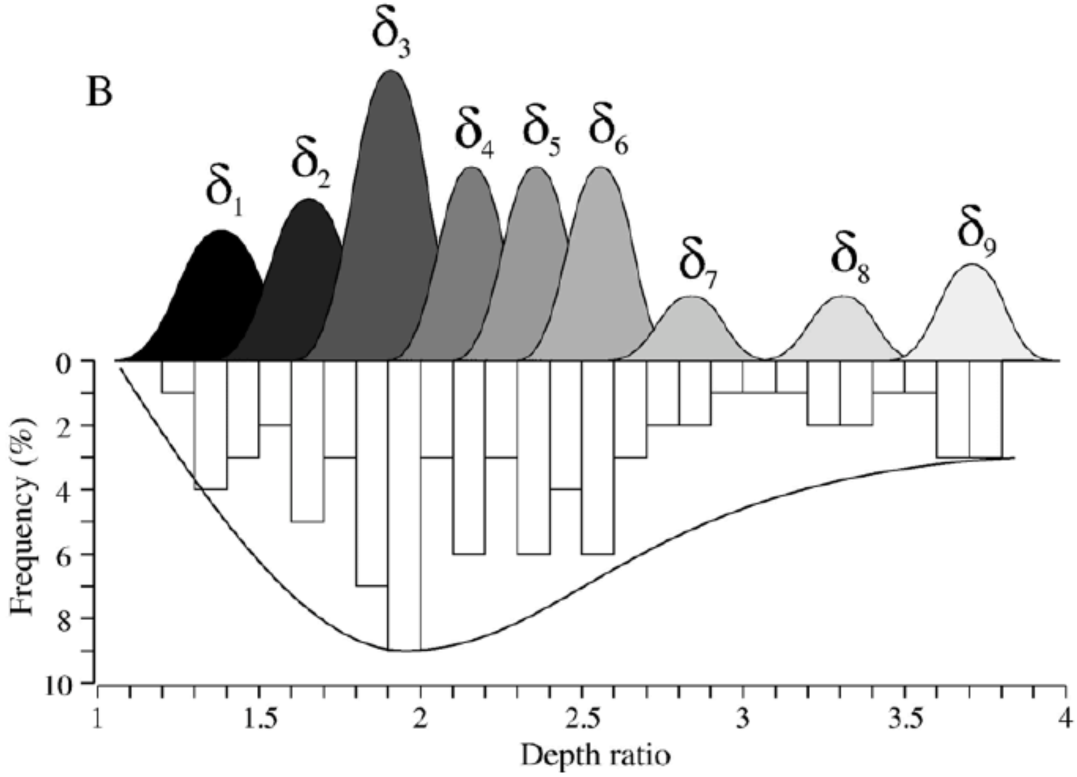

Figure 16. The frequency distribution of d ratios from El Yelmo, Spain separated into small sets of gnammas with similar d ratios where d_1, d_2 . . . d_9 represent nine different sets of d values from 100 field readings (Domínguez-Villar, 2006, p. 144).

The frequency distribution of d ratios were examined closely in these papers and subsets were chosen by inspection (Figure 16). Each of these sets was shown to have Gaussian distributions (Domínguez-Villar, 2006, p. 144; Domínguez-Villar and Jennings, 2008, p. 171; and Domínguez-Villar et al., 2009, p. 225). This is a process that is strongly condemned by teachers of statistics because this patchiness of the data is caused by sampling small numbers of data, not by real differences in sets of data. However, it is claimed that these subsets of d ratios represent different period of the initiation of gnammas on these surfaces, which is geologically possible.

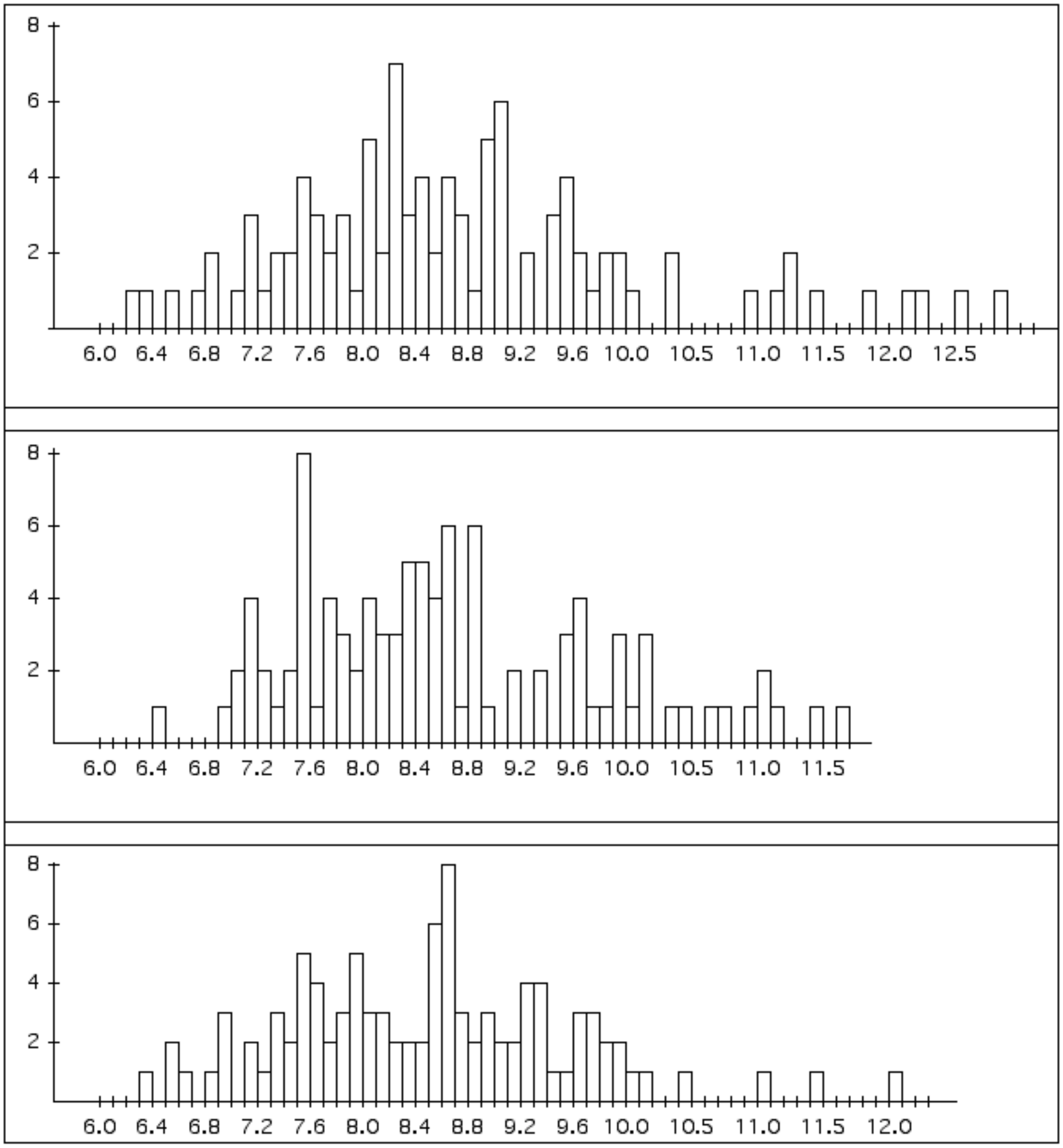

Figure 17. The horizontal axis is in unitless d ratios. The vertical axis is in the number of examples of each d ratio of that size. Three separate sets of simulations of the d ratio of gnammas from model 2. Each set represents 100 simulations with the same starting parameters and the same rates of weathering and the same underlying random Gaussian weathering mean and standard deviation.

Figure 17 shows three sets of 100 simulations each, in which all the deterministic parameters were identical and the underlying mean rate of weathering was 1 mm per year with a standard deviation of 0.5 mm/year. All the simulations were run for 400 years during which time the d ratio came to a steady state of about 9 units. All of the artificial gnammas were 400 years old but they have very different d ratios due to random events in the model. If the simulation had been performed 10,000 or 100,000 times, the frequency distributions would have been smooth continuous asymmetrical curves (see the smooth curves in Figures 14 and 16) but these sets of 100 simulated gnammas (Figure 17) seem to have subsets although there are no underlying subgroups of younger gnammas in these simulations.

Readers with only the top set of 100 gnammas (Figure 17) would find different subsets from readers presented with the middle diagram or the bottom diagram. The largest sets of real data collected in the studies addressed here were 100 gnammas in Portugal (Domínguez-Villar and Jennings, 2008, p. 170). The set from Minnesota had 85 gnammas (Domínguez-Villar et al., 2009, p. 222), and the set in Chile had only 16 gnammas (Domínguez-Villar, 2006, p. 141). It looks as if Domínguez-Villar et al. have been mislead by the patchiness of their own sampling which look like sets of different age gnammas but are more likely gnammas all of the same age but different growth rates due to many different random processes. It would be better to have more gnammas but there are constraints at the outcrops due to lack of gnammas, and logistical practicalities, as well as their own conscious and unconscious rules for excluding gnammas from their samples.

Some Computer Modeling Comments for Readers Who are not Modelers

Model 1 was made to reproduce the behavior of gnammas with a spillway that is deepening faster than the gnamma. It would have been surprising if the model had not behaved that way. I suspected that the model would not reproduce the correlations between h and u that Domínguez-Villar had reported in all his field areas (Figure 3). This suspicion was confirmed. So, just as in the rest of science, when some very clear numerical data is incompatible with a theory, that theory is almost certainly incorrect.

The original scenario (number 1) seemed forced to me. It did not explain why the rate of spillway deepening became faster than the deepening of the gnamma. In fact, that seems unlikely as the gnamma is wetter more of the time. I tried the model with a gnamma that deepened faster than the spillway. In order to do this, we must completely reverse our image of the history of the gnamma. This second scenario (number 2) worked, it reproduced Figure 3 but it did much more, it explained the stability, and the probability density distribution of the d ratio, both of which had been noted by Domínguez-Villar in all his field studies.

The model of the gnamma does not seem very complex, but the stability of the d ratio was a surprise. Computer models are often used to model very complex systems such as the atmosphere, the ocean, a city, the national economy, or the physiology of a human body. It is not surprising if these models produce many behaviors that were not expected by the modelers. J. W. Forrester (b. 1918), one of the inventors of the computer and the founder of digital computer modeling, wrote that we should have great trust in model that is complex enough to produce counterintuitive behavior that is like the data from the real world (1971). The unexpected stability of the d ratio, in the model and in the real data, gives the computer modeler (and I hope the reader) great confidence in model 2.

Domínguez-Villar used the d ratio. He believed that d was a good timer for gnamma development. He found d was often very stable, as if sets of gnamma were initiated at different times. Domínguez-Villar did not invent the d ratio; it was developed by Juan Ramón Vidal Romani in his 1983 doctoral thesis. Computer modeling students are discouraged from using ratio measures of system performance, especially if the denominator becomes small, which makes the ratio swing wildly. If the denominator becomes zero, as does the u value, the model is not computable and will stop running. I was very surprised that Domínguez-Villar reported that the d ratio was so similar in real gnammas on one outcrop but the model shows us that the d ratio really is stabile. Furthermore, the model shows us that this stability does not tell us about the age of the gnamma but about the average rate of weathering. Thus, Domínguez-Villar has unwittingly given us an interesting new measure of the rate of weathering.

Domínguez-Villar reported that almost all of the frequency distributions of d ratios on surfaces were skewed to the low side. These look "log normal" (a Gaussian distribution with all the numbers raised to some exponent such as 10), but it is hard to tell from his reports. Tafoni are known to be log normal (Norwick and Dexter, 2002; Achyuthan et al. 2010) and gnammas sometimes act like tafoni (Hall and Phillips, 2006). Domínguez-Villar had shown that the simplest and youngest gnamma have d ratios distributed as a bell shaped curve - that is Gaussian. The computer models incorporated his belief by using Gaussian distributed rates of weathering of the gnamma and spillways. However, the resulting d ratios in the models are skewed to the small side with a few scattered large reading on the right (Figure 15 and 17) just as are the real data (Figure 14 and 16), another unexpected characteristic of the model which is like the real world.

Domínguez-Villar and his predecessors believed that they could subdivide their data in to sets of gnammas with different d ratios. They believed that the d ratio was a measure of the age of the gnammas. They believed that they could differentiate several, sometimes as many as nine different periods of gnamma initiation, perhaps due to critical factors during past climates. Model 2 shows that this apparent clumping (Figures 14, 15, 16, 17) is only a matter of the limited samples possible in the field, or limits in the patience of the geomorphologist collecting data. By Occam's Razor, if for no other reason, I hope the reader will agree with me that scenario two is the theory we could accept.

The real test of this can be found on any surface with gnamma or tafoni. Surfaces of 10 to 400 years generally have many small pits (Norwick and Dexter, 2002; Achyuthan et al. 2010). Except in the spray zone of the ocean, gnamma and tafoni on surfaces developed over a few thousand years are several cm across and do not have tiny gnammas between the large pits. On surfaces that are millions of years old, the gnammas are meters across and do not have gnammas of a mm or a cm between the large gnammas. If this is true, it is good news. There is something happening on these surfaces that prevents pitting. If we can discover what is really happening, perhaps we can develop artificial processes that can protect buildings, statues, that are great cultural treasures from the ravages of time.

Professor Heather Viles[i] wrote that there should be more computer simulations of stone weathering studies. I hope this paper will contribute to an understanding of the negative and positive roles that computer models can have in understanding mistaken theories, and in constructing new and much better theories.

Geomorphic Discussion

Which scenario is responsible for armchairs (see definition above)? No one has ever reported an armchair less than 100 mm in diameter. Most photographs of armchairs in Domínguez-Villar's dissertation (2007) are more than a half meter across. This suggests that armchairs are old. It is a shame that Domínguez-Villar not only dismissed armchairs from his numerical field work, but even near armchairs. Just what happens if a spillway becomes deeper than its gnamma? We need to understand these features. The author has observed giant armchairs along the Côte de Granit Rose of northern Brittany that might be good to study.

The problem is not just the errors that may have been made by Domínguez-Villar and the workers who preceded him in using the d ratio. The main issue to me is whether weathering pits are initiated continuously, or in episodes, or mostly at the beginning of weathering. In many cases, on sea coasts, in the spray zone, tafoni and gnammas form continuously or in episodes and cycles. The pits there grow faster parallel to the surface and soon obliterate themselves. A new, almost fresh rock surface is exposed, and tafoni and gnammas form for a new cycle of enlargement and obliteration. But this may only be characteristic of the coastal spray zone. Certainly it is unlike the periglacial gnammas in the three papers discussed above (Pestrong, 1979, 1980, 1988).

However, studies in the Arizona desert (Norwick and Dexter, 2002), in the tropics of southeast India (Achyuthan et al., 2010), periglacial surfaces in Scotland (Hall and Phillips, 2006), and recent as yet unpublished work by the author in the temperate forests of Brittany France show that tafoni and gnammas often initiate after a few centuries, and after that there are few if any new tafoni or gnammas. The photographs in the papers of Domínguez-Villar, and especially his dissertation, show numerous outcrops which seem to show large gnammas and armchairs with no small gnammas or tafoni between them.

Domínguez-Villar has presented three papers that purport to show that gnammas are initiated on granitic periglacial surfaces around the world in episodes. If the new analysis in the present paper is correct, the periglacial gnammas described in the papers by Domínguez-Villar are more likely initiated a few hundred years after deglaciation, and not in episodes after that. The difference in the depth, length, width, and water holding capacity of gnammas is more likely due to minor differences in rock properties which caused the average rate of weathering to differ from place to place and that caused the d ratio steady state to vary over the outcrop, producing gnamma with different geometries and d ratios.

I believe the reader will be convinced by the numerical facts from the real data and the simulations. The next step is to test the new, more likely correct model probably using cosmogenic radio-isotopes. This has already been done in Scotland by Hall and Phillips (2006), but the data needs to be recollected or perhaps only reorganized to test the theory from model 2. In Brittany, the features sometimes start as channels and then gnamma develop in the deeper parts of the channels, but in other places there are gnamma without spillways (Sellier, 1997). We are preparing to do cosmogenic age studies of gnamma and armchairs in Brittany using natural outcrops and also the menhirs of Erdeven, Carnac.

Domínguez-Villar and his colleagues have discovered some very useful outcrops for understanding gnamma development in periglacial environments. They could use these field areas to great advantage. For example they seem to believe that gnamma do not enlarge or change shape in length and width very much from the initial depressions that caused the gnamma. This seems unlikely on several accounts. Initial randon depressions on newly exposed rock surfaces are generally quite irregular. Domínguez-Villar and many workers before him find that gnammas and tafoni are usually very close to circular ((Domínguez-Villar, 2006, p.142; Domínguez-Villar and Jennings, 2008, p.171; Domínguez-Villar et al., 2009, p.224). This was most likely caused by weathering and erosion into the sides of the gnamma. A study of the dimensions of gnammas on Domínguez-Villar's field sites would greatly enlarge our understanding of periglacial gnamma.

From the modeling perspective the next step is to incorporate more of our understandings of gnamma and tafoni development. Hall and Phillips (2006) have demonstrated that gnammas in Scotland, like tafoni in Arizona, Tamil Nadu, and Brittany, enlarge by sigmoidal equations. This can be incorporated into the model, and it will certainly cause the rate of weathering of the gnamma and its spillway to develop in more complex, perhaps even more realistic ways.

Every year, around the world, tens of billions of dollars of damage is done to buildings, statues, bridge abutments and other stone structure. In some cases objects of great value to all humankind are endangered. The growth of gnammas and tafoni must be understood and prevented.

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