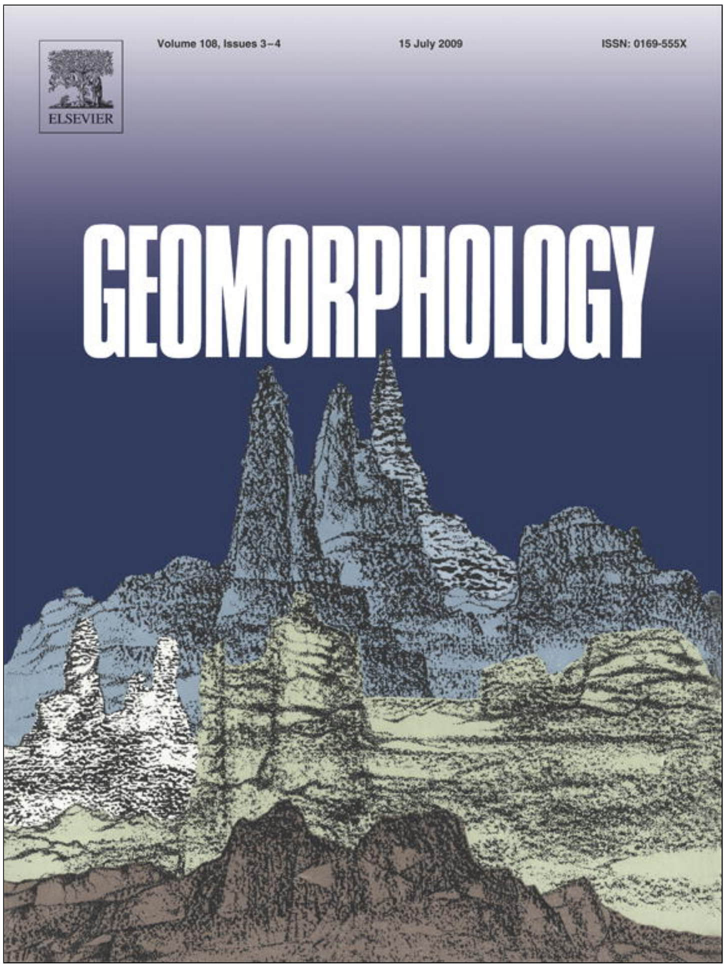
Volume 108, Issues 3–4
15 July 2009
ISSN: 0169-555X
ELSEVIER
GEOMORPHOLOGY

Geomorphology 108 (2009) 200–208

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Erosional decay of the Yucca Mountain crest, Nevada

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ARTICLE INFO

Article history:
Received 19 June 2008
Received in revised form 15 January 2009
Accepted 16 January 2009
Available online 13 February 2009

Keywords:
Erosion modelling
Yucca Mountain
Nuclear waste deposit
Digital elevation model
Stream power

ABSTRACT

A simple numerical landscape evolution model is used to investigate the rate of erosional decay of the Yucca Mountain crest in Nevada, USA — a location proposed as a permanent repository for high level radioactive waste. The model is based on a stream power approach in which we assume that the rate of erosion is proportional to the size of the catchment as a proxy for water flux and to the square of the topographic gradient. The proportionality constants in the model are determined using the structural history of the region: extensional tectonics has dissected the region into a series of well-defined tilt blocks in the last 11 my and the ratio of fault displacement and gully incision during this time is used to scale the model. Forward predictions of our model into the future show that the crest will denude to the level of the proposed site between 500,000 years and 5 my. This prediction is based on conservative estimates for all involved parameters. Erosion may be more rapid if other processes are involved. For example, our model does not consider continuing uplift or catastrophic surface processes as they have been recorded in the region. We conclude that any "total system performance analysis" (TSPA — as has been performed for the Yucca Mountain region to predict geological events inside the ridge) must consider erosion as an integral part of its predictions.

1. Introduction

Yucca Mountain in Nevada (USA) (located at about 36° 51′ N. and 116° 27′ W. northwest of Las Vegas) is a site suggested by the U.S. government as a permanent repository for high level radioactive waste (Fig. 1) (U.S. Department of Energy, 1988). As a consequence, a series of investigations over the last few years have studied the geology of the region. Particular focus has been made on the deformation history to investigate if the major structures in the region are active and if, therefore, they propose an active threat to the site (Morris et al., 2004; Potter et al., 2004; Wernicke et al., 2004; Hill and Blewitt, 2006). The erosional history on the other hand has only been studied with respect to the documentation of erosion features (e.g., Coe et al., 1997) and the climatic history (e.g., Forester et al., 1999), but no forward predictions of the incision rates of the valleys have been made. In this paper, we investigate the rate at which the Yucca Mountain crest may decay in response to erosion using numerical modelling. In particular, we study the time that individual gullies may take to penetrate to the depth of the proposed waste deposit site. Our results are compared with some morphological observations described in the literature.

2. Geology and geometry relevant for the modelling

Geologically, Yucca Mountain is located along the southwestern border of the Basin and Range province of the western USA in the Walker Lane Belt. The entire Basin and Range province is well known for its extensional tectonic setting and associated volcanism (Ellis et al., 1999; Sonder and Jones, 1999). In the Yucca Mountain region, this volcanism is expressed as a series of Miocene calderas that are part of the Southwest Nevada Volcanic Field (Fig. 1A). These calderas were mostly active in the time between 15 and 9 my depositing pyroclastic flows and ashes that are known as the Paintbrush Group (Fig. 1C). Rocks of the Paintbrush Group form the principle rock types at Yucca Mountain (Sawyer et al., 1994; Fleck et al., 1996; Potter et al., 2002). Three volcanic units are of relevance to the site: the Topopah Spring Tuff of the Paintbrush Group hosts the proposed nuclear waste deposit site. It erupted around 12.8 my and is about 300 m thick (Day et al., 1998). Above it, the Tiva Canon Tuff (also of the Paintbrush Group) erupted at 12.7 my and is about 100–150 m thick. The Tiva Canon Tuff forms most of the surface exposure in particular along the topographic ridges. Finally, the Rainier Mesa Tuff of the Timber Mountain Group forms the youngest known volcanic in the region. It erupted at 11.6 my, it is between 0 and 200 m thick, but it is only preserved as a small region outside the Yucca Mountain ridge itself. The Rainier Mesa Tuff may not have covered the entire sequence uniformly as it overlies the Paintbrush Group unconformably.

The volcanic sequence is dissected by a series of mostly west-dipping normal faults that divide the mountain into 1–4 km wide blocks that are tilted to the east (Potter et al., 2004). Block-bounding faults were active at, during, and after deposition of the 12.8–12.7 my Paintbrush Group. For example, the 11.6 my Rainier Mesa Tuff is deposited with an 8°–10° angular unconformity onto the Paintbrush Group (Scott, 1990). Nevertheless, significant motion on the faults, including about 15° tilting of the blocks, postdated the 11.6 my Rainier Mesa Tuff (Potter et al., 2002). Although diminished fault activity continued into Quaternary time (Scott, 1990), Potter et al. (2004) suggested that most of the displacement along the faults occurred between 11.6 and 11.45 my and correlated with

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doi:10.1016/j.geomorph.2009.01.008

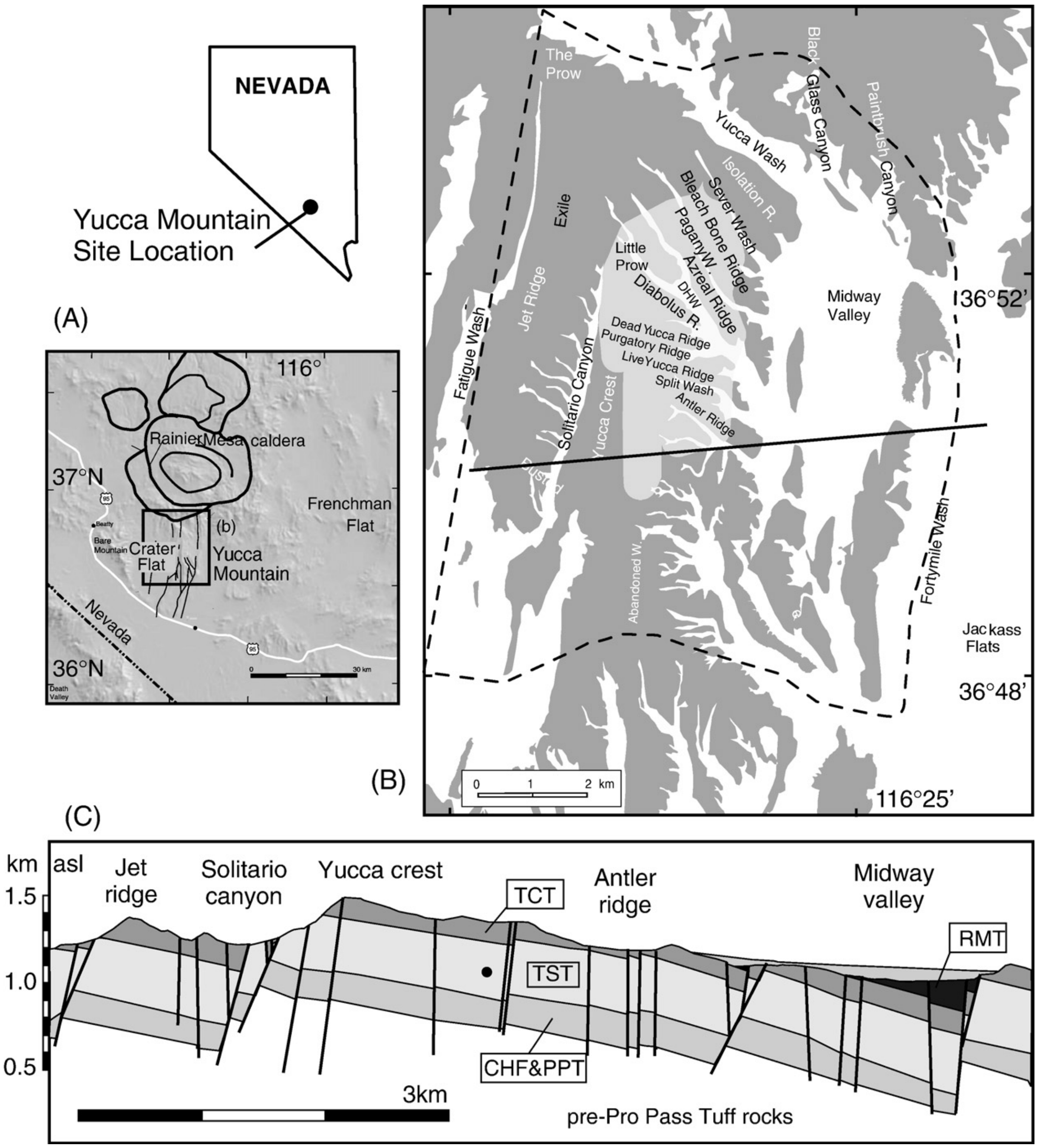

Fig. 1. Location and geology of the Yucca Mountain region (modified after Potter et al., 2004). (A) Location of the Yucca Mountain site in relation to the Calderas of the Southwest Nevada volcanic field. (B) The Yucca Mountain site area. Miocene volcanic bedrock exposure is shown in dark grey, location of the waste deposit site in light grey. (C) Topographic and geological cross section as indicated on (B). The location of the proposed waste deposit site is shown as the black dot. Geological units are RMT = Rainier Mesa Tuff; TCT = Tiva Canon Tuff; TST = Topopah Springs Tuff; CHF&PPT = Calisto Hills Formation and Prow–Pass Tuff.

a vertical axis rotation of the region. The displacement along the faults was up to 500 m at the maximum (Morris et al., 2004). The proposed site within the Topopah Group is located 250–375 m below the surface and about 250 m above the water table (Fig. 1C).

Morphologically, the Yucca Mountain ridge reflects the block tilting to the east: principal topographic ridges strike north–south and have short west- and long eastern slopes (Fig. 1). Relief is 300–500 m between the ridge crests at about 1500 m above sea level (asl) and the main valleys (locally called "washes") at about 1000–1200 m asl. The Yucca Mountain waste deposit site itself is located in the principal ridge bounded to the west by the Solitario Canon Wash and to the east by the Midway Valley of the Yucca Wash. East-facing slopes largely follow the tilt block surfaces, while the steeper west-facing slopes cut across the stratigraphy. The Rainier Mesa Tuff is completely eroded except in the valley floors. However, about half of the block tilting occurred prior to the deposition of the Rainier Mesa Tuff, so that its thickness varies substantially and we do not know how thick it may have been on top of the topographic ridges outside the preserved regions in the half grabens. West–east running gullies from the principal ridge crest toward the Yucca Wash are of the order of 50-m relief and are locally known (from north to south) as Pagany Wash, Drill Hole Wash, Split Wash, and Whale Back Wash (Fig. 1).

3. Model set up and boundary conditions

In order to model the erosional evolution of the Yucca Mountain crest, we made some very simple assumptions on the governing

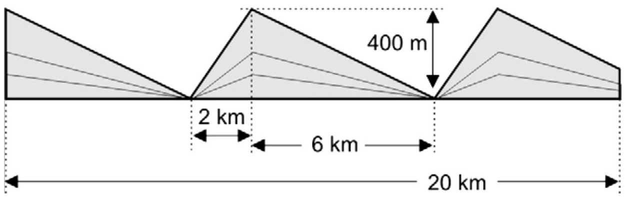

Fig. 2. Geometry of the simplified model used to scale the erosion parameter. The final geometry is reached after 8 my in the model. Over time, the uplift rate is assumed to be constant.

physical erosion processes and implemented those into a landscape evolution model (LEM). This LEM was then applied to the topography at Yucca Mountain using the 1-arc-second digital elevation model (DEM) of the region. Scaling of the proportionality constants in the model was performed by using the duration of faulting to create the tilting of blocks. Using the best fitting proportionality constants, we estimated the duration of erosional decay of the crest. For our model, we assumed that erosion can be related to stream power, s, where s is defined as

$$s = A^{\theta} \times \left(-\frac{dH}{dL}\right). \quad (1)$$

In this equation, dH/dL is the topographic gradient of elevation H with channel distance L along a channel, and A is the size of the upstream drainage area as a proxy for water flux in the stream. The exponent θ defines the nonlinear relative contributions of slope and area. θ is called the concavity index and has been determined to be between 0.25 and 0.6 for many catchments around the world (Hack, 1957; Tucker and Whipple, 2002, for a review).

The relationship between stream power and erosion rate is not trivial. For channels in geomorphic equilibrium, linear and quadratic relationships between stream power and erosion rate render identical channel profiles: equilibrium channels can therefore not be used to derive this relationship. Conversely, for nonequilibrium channels, not enough information on their time dependent evolution is available to constrain this relationship. In absence of better constraints, Wobus et al.

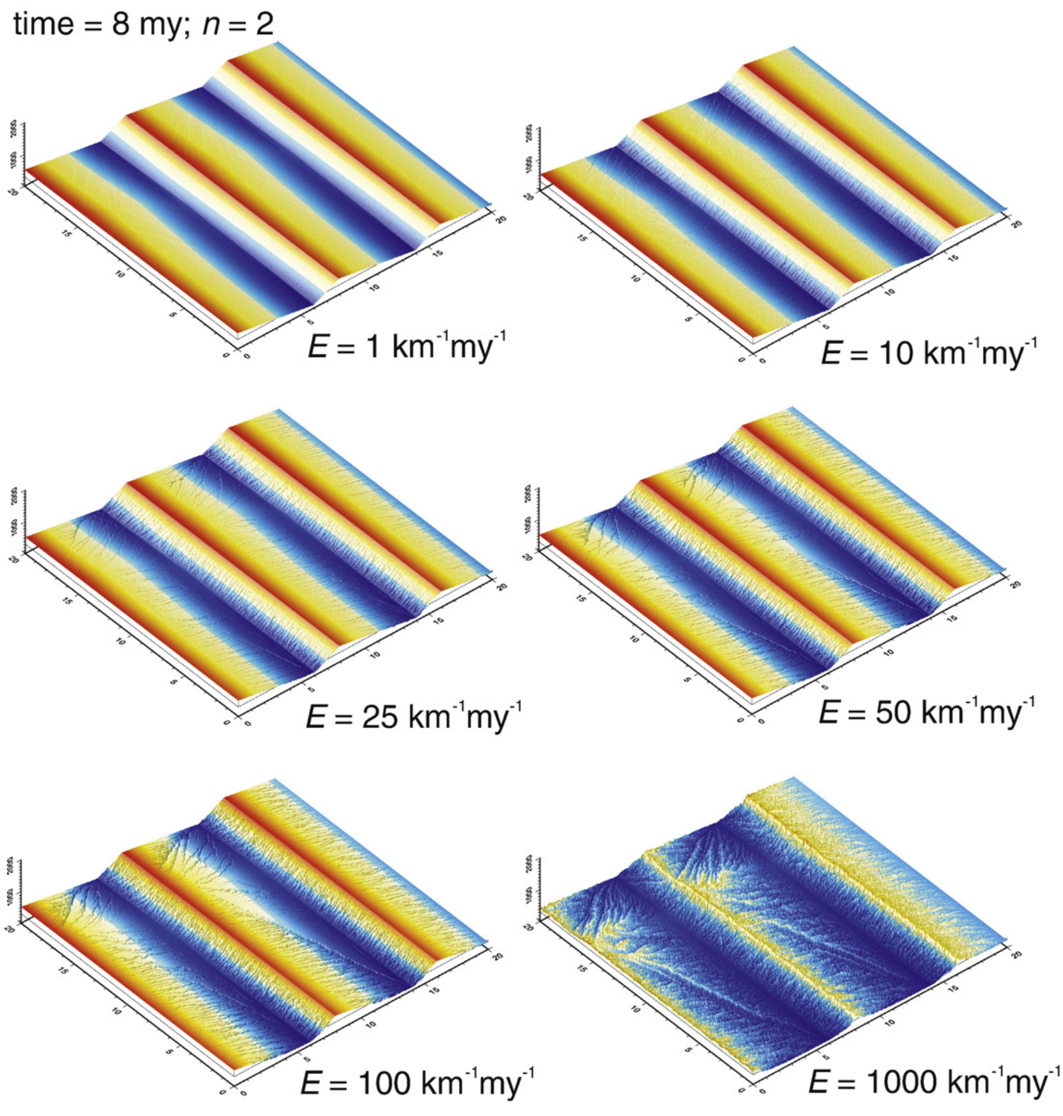

Fig. 3. Three-dimensional illustration showing the final result (after a nominal 8 my) of the simplified scaling model (Fig. 2) for six different erosion parameters. The topography in the bottom two diagrams resembles best the observed topography (Fig. 1), suggesting that the erosion parameter is between $E = 100$ km^{-1} my^{-1} and $E = 1000$ km^{-1} my^{-1} corresponding to an erosion rate of 1–10 mm/year in gullies draining a 1-km^2-sized catchment with a topographic gradient of 10%. Colour coding from blue to red corresponds to 0 to 400 m above the deepest valley floors.

(2006) assumed that erosion rate is directly proportional to stream power. In contrast, in the engineering literature, a power law relationship is generally assumed so that

$$erosionrate = -\frac{dH}{dt} = Es^n. \tag{2}$$

Here we follow Hergarten (2002) and Stüwe et al. (2008) and assumed that erosion rate is proportional to the square of stream power so that $n=2$. Using a mean concavity index of $\theta=0.5$, this resulted in

$$erosionrate = -\frac{dH}{dt} = E \times A \times \left(\frac{dH}{dL}\right)^2 \tag{3}$$

where we call the proportionality constant E the erosion parameter. This erosion parameter has the units of $E=\text{km}^{-1}\ \text{my}^{-1}$ and includes all material constants and climatic variables. An erosion parameter of $E=100\ \text{km}^{-1}\ \text{my}^{-1}$ corresponds to an erosion rate of 1 mm/year in gullies draining a 1-km^2-sized catchment with a topographic gradient of 100 m/km. Eq. (3) was used here for the numerical modelling, and it is applied to all nodes of the digital elevation model. Some consideration of more refined models and their influence on the results is presented in the discussion section.

3.1. Scaling of the erosion parameter

In order to scale the model (largely by scaling the parameter E), we used the structural history as a time marker: we made a cartoon Fig. 2 of the structural evolution for the time between the eruption of the Paintbrush Group (12.7–12.8 my) and the present time and let our LEM erode this model over time using a series of proportionality constants until the modelled drainage system resembled the observed wash geometry. For all geometrical parameters and timescales, we simplified the model in a way so that the resulting erosion rate estimate is an absolute minimum with realistic erosion rates being up to an order of magnitude higher.

For the geometry, we assumed a block 20×20 km in size. This block was divided into three similar ridges that were assumed to build over time to describe tilting as shown on Fig. 2. The time of tilting was assumed to be 8 my as a minimum time of fault activity between the eruption of the Rainier Mesa Tuff (11.6 my) and the Quaternary when faulting became much less active. Uplift during this time was assumed to be 400 m corresponding to a mean displacement rate of 0.05 mm/year along the block bounding faults, consistent with measurements of Morris et al. (2004). Erosion was modelled for $E=1, 10, 25, 50, 100$, and $1000\ \text{km}^{-1}\ \text{my}^{-1}$ and was assumed to act at all times, during the block tilting and thereafter.

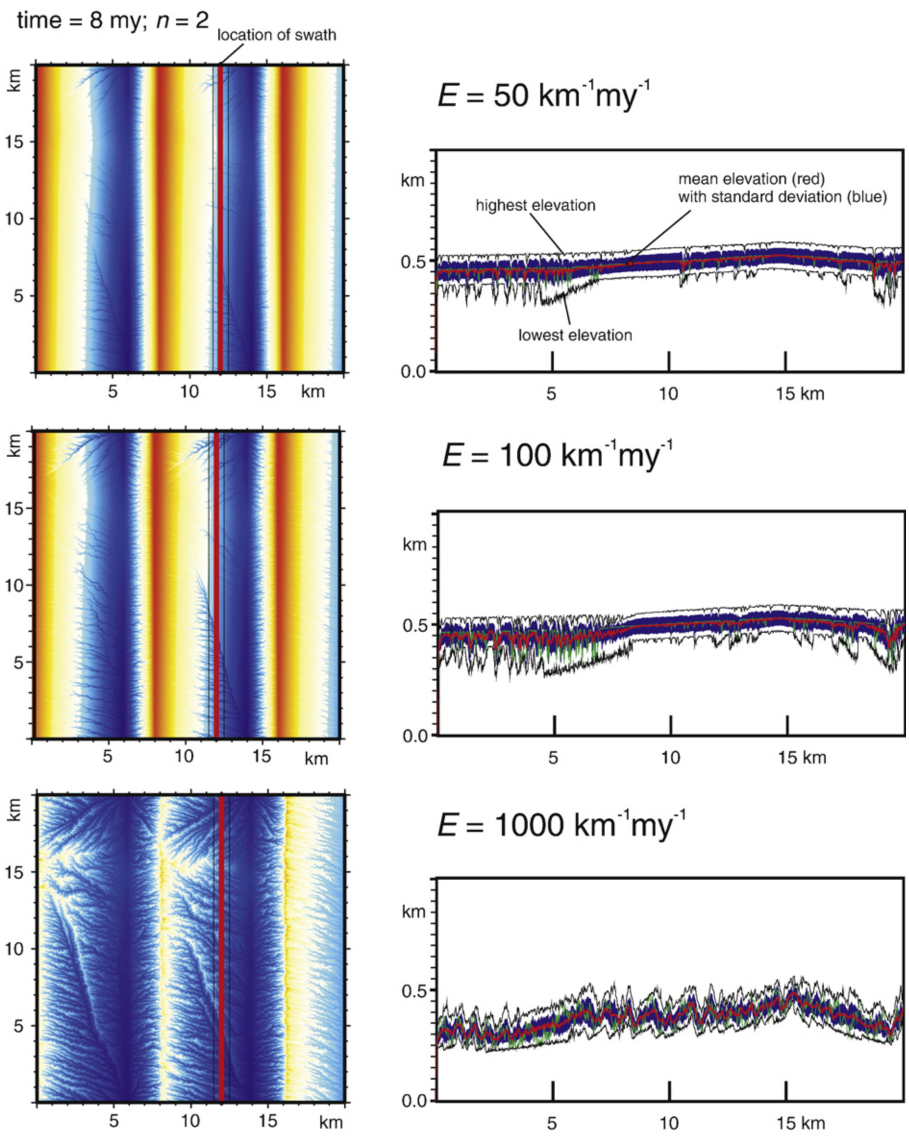

Fig. 4. Planview illustration of the model shown in Fig. 3 and topographic swath profiles along the midslope of the principal ridge (red line).

Fig. 3 shows the morphology at the end of the tilting time (i.e., after 8 my time). By comparison with the real morphology of the Yucca Mountain ridge, it may be seen that erosion parameters between $E = 50$ km^{-1} my^{-1} and $E = 1000$ km^{-1} my^{-1} may be appropriate. For a more quantitative interpretation of the best fit erosion parameter, Fig. 4 shows topographic swath profiles along the hill front for the three higher erosion parameters on Fig. 3. Each swath is drawn around a central line 2 km from the valleys and 4 km from the ridges and is 1 km wide. These swath profiles may be compared to the actual topography as shown on Fig. 5 (top left). The swath through the present day topography (Fig. 6, top) shows that there is usually about 50–100 m relief along the swath. Importantly, at the position of the swath, the entire surface of the Tiva Canon Tuff is dissected so that no flat surfaces remain. In comparison, the model cartoon for $E = 50$ km^{-1} my^{-1} shows that much of the east slope of the Yucca Mountain main ridge remains intact with only individual narrow gullies incising locally up to 100 m below the upper contact of the Tiva Canon Tuff. What appears on the swath as a single broader valley at 5 km is the oblique intersection with the largest valley formed at this stage, For $E = 100$ km^{-1} my^{-1}, about 200–300 m relief developed along the side of the range that corresponds to the relief observed at Yucca Mountain. However, substantial parts of the western side of the swath (upper black line, maximum values) remain still intact, which is not the case at Yucca mountain. Only for $E = 1000$ km^{-1} my^{-1} is the entire Yucca Mountain ridge heavily disected with the relief being of the order of 200 m.

We conclude that the erosion parameter for Yucca Mountain lies between $E = 100$ km^{-1} my^{-1} and $E = 1000$ km^{-1} my^{-1}. For the following calculations we present the results for $E = 100$ km^{-1} my^{-1}, keeping in mind that erosion parameter E and erosion time are directly proportional. In other words, doubling the erosion parameter results in doubling of the erosion rate.

4. Results

We have now used the derived minimum estimate for the erosion parameter of $E = 100$ km^{-1} my^{-1} and let Eq. (3) act on the 1-arc-second DEM of Yucca Mountain (Figs. 5 and 6). As fault ativity appears largely diminished in the Pleistocene, we have inserted no

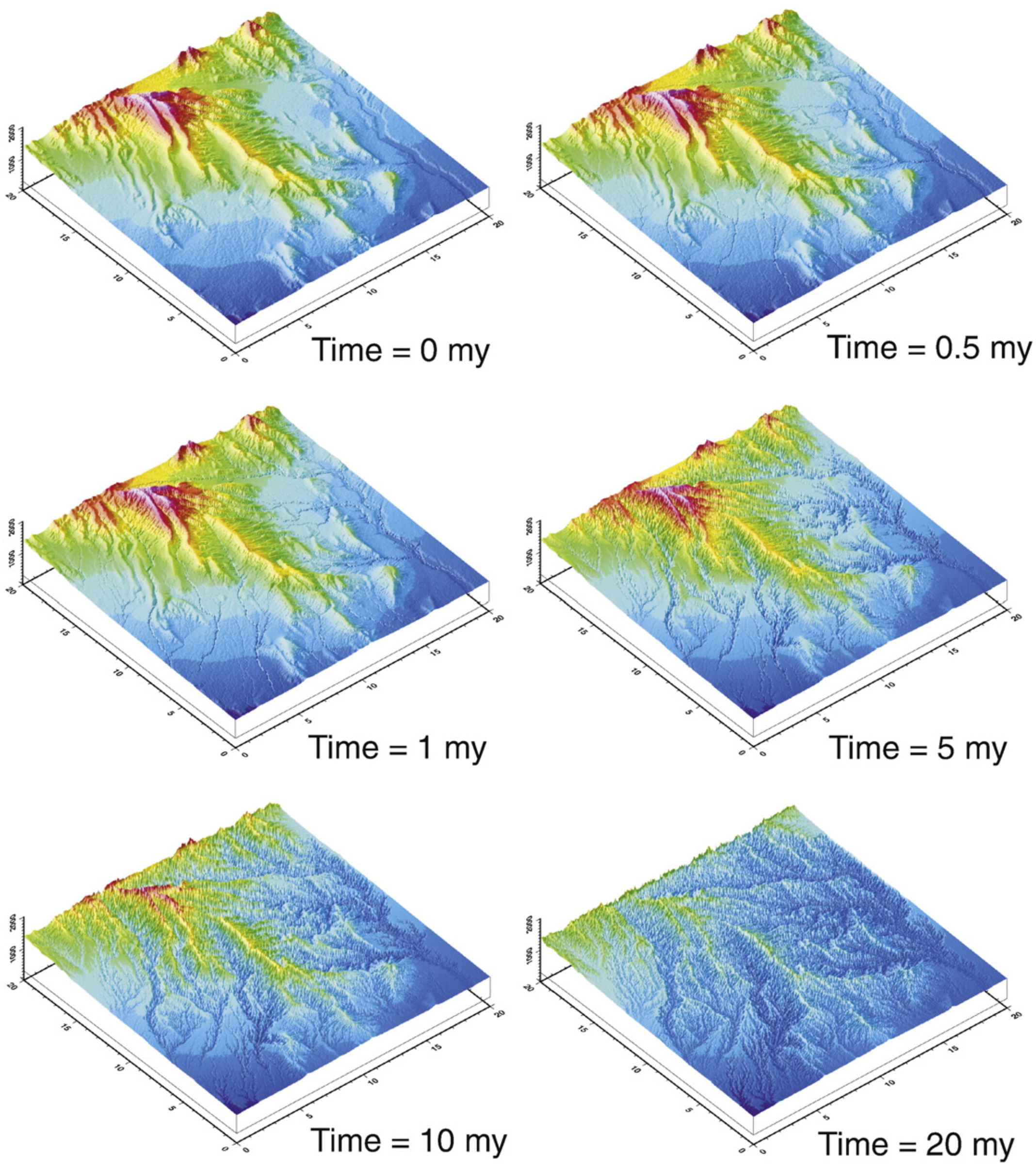

Fig. 5. Erosional decay of the Yucca Mountain crest projected into the future. Note that the shown times scale directly with E, so that for $E = 1000$ km^{-1} my^{-1} all labelled times are a factor of 10 shorter. The entire figure is for $E = 100$ km^{-1}my^{-1}; $n = 2$.

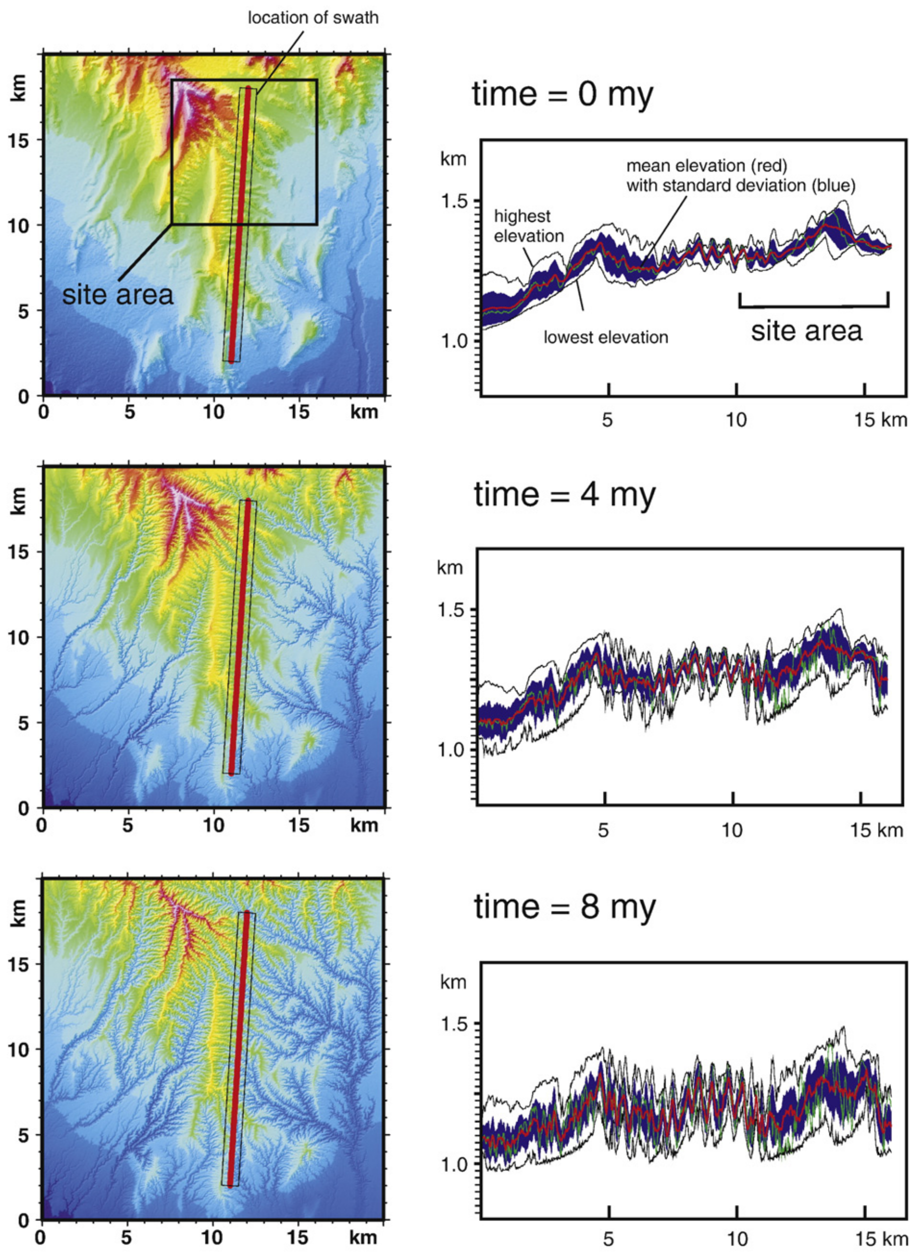

Fig. 6. Planview illustration and topographic swath profiles along the midslope of the Yucca Mountain of three time steps from the same model run as shown in Fig. 5. Time steps are slightly offset from Fig. 5 to present extra information. In the swaths, green is the topography along the central line of the swath, red is the mean over the width of the swath, blue is its standard deviation, and the thin black lines show minimum and maximum elevation over the width of the swath. The entire figure is for $E=100$ km^{-1}my^{-1}; $n=2$.

uplift function but performed our predictions for the future evolution by letting erosion passivly denude the present day topography. Fig. 5 show the predicted evolution projected to 20 my into the future. In all further discussion, note that the erosion rate scales linearly with the assumed erosion parameter. That is, for $E=1000$ km^{-1} my^{-1}, (instead of $E=100$ km^{-1} my^{-1}), the images on Fig. 5 show times between 0 and 2 my. It may be seen that there is little apparent change within the first 1 my, but that the entire Yucca Mountain region is substantially denuded after 5 my (or 500,000 years for $E=1000$ km^{-1} my^{-1}). At 20 my, practically no topography is left. The qualitative interpretation of Fig. 5 can be much better seen on the swath profiles of Fig. 6. These profiles show that (for $E=100$ km^{-1} my^{-1}) after 4 my about 200 m relief developed on the slopes of Yucca Mountain. At 8 my, the entire ridge is heavily disected.

Whether or not this erosion affects the proposed waste deposit site is best interpreted by studying the total amount of erosion that is predicted into the future by our model (Fig. 7). Fig. 7 shows only the subregion of Figs. 5 or 6 where the waste deposit site is proposed with the most important washes labelled. Interpreting the results again in terms of the minimum erosion parameter $E=100$ km^{-1} my^{-1}, it may be seen that the entire region is denuded by about 500 m in 20 my. However, even after 1 my, incision of about 200 m has occurred in the Solitario Canyon, the Drill Hole Wash, and the Yucca Wash.

5. Discussion

The calculations have shown that the Yucca Mountain crest will erode within 5 my to the level proposed for the waste deposit site using a minimum erosion parameter of $E=100$ km^{-1} my^{-1} or in 0.5 my for a not unrealistic erosion parameter of $E=1000$ km^{-1} my^{-1}. Clearly these estimates are only for incision of the surface to the depth of the waste deposit site, and the influence of erosion on the

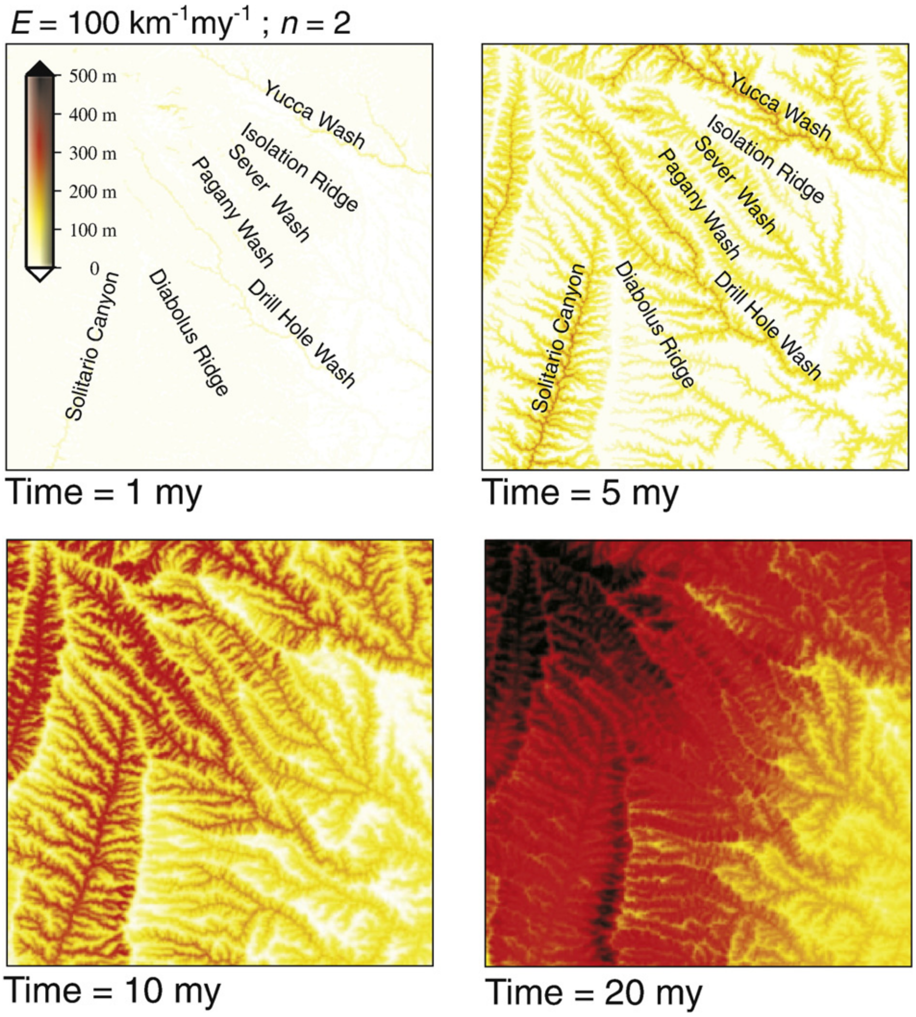

Fig. 7. Total amount of denudation from the Yucca Mountain crest predicted over time in the subregion indicated by the box on Fig. 6 top left. After 5 my, most of the major washes have incised about 200 m vertical, which is the level of the proposed waste deposit site.

hydrology of the system will begin much earlier. Nevertheless, three factors may be outlined that can influence this result and require discussion: (i) for all assumptions, we used minimum values for the parameters so that the estimated erosion time represents an absolute maximum; (ii) our conclusion was drawn from a continuum model assuming constant erodibility, as described in our model through the erosion parameter *E*. Erodibility of the material and climatic changes may cause changes over time that are not considered here. (iii) The model assumed here may simply be wrong. These three aspects are now discussed.

5.1. Minimum estimates

The estimates presented above were scaled using the model shown in Fig. 2. In this model, block tilting is described by a variable uplift function in which the slope of both sides of each block increases with time and the length of the slope increases with the cosine of tilt. In reality, block tilting involves a slightly different geometry: the western slopes are likely to be successively exposed at a constant tilt angle while the eastern sides will only be tilted and not stretched. However, the model geometry assumed here (Fig. 2) provides lower erosion rate estimates than would a proper two-dimensional consideration of tilting. Thus, the estimated erosion parameter is probably at the low end of the realistic range. Subsequent erosional decay of the crest was modelled assuming that no further uplift occurred in the region.

Most important of all estimated boundary conditions is the thickness of the Rainier Mesa Tuff. In our model, we assumed that the Rainier Mesa Tuff never covered the entire crest of Yucca Mountain and that, therefore, the observed depth of incision of the gullies reflects the entire incision since block tilting. Looking at Fig. 6 (time 0 at top), it may be seen that north–south profiles along the eastern slope of the crest have no flat sections, suggesting that the entire former surface is gone. If this is the case, then there is a possibility that the Rainier Mesa Tuff once covered most of the ridge and it is impossible to infer how much section was lost. The maximum thickness of the Rainier Mesa Tuff is estimated to be 200 m (Potter et al., 2004). If indeed some of this thickness was present in the past at the present day crest of the ridge, then our calculations may be a significant underestimate of the real erosion times.

It is also important to consider the fact that surface incision to the level of the waste deposit site is only an upper limit to the time of acute danger. Once the covering Tiva Canon Tuff (TCT) is incised to expose underlying units, the highly fractured Paintbrush Tuff and underlying Topopah Springs Tuff (TST) are exposed to surface processes, possibly causing dramatic changes in the hydrology of the ridge. Again, this implies that our estimates form an upper bound.

5.2. Variable erodibility

The results presented above are based on assuming a constant value for the erodibility *E*. In the field, rocks of the Tiva Canon Tuff (TCT on Fig. 1C) and Topopah Springs Tuff (TST on Fig. 1C) probably have a similar erodibility. However, there is a thin, nonwelded tuff unit–the Paintbrush Tuff–located between TCT and the TST that is known to erode extremely rapidly if exposed. Clearly this also indicates that our estimates must be considered as a minimum.

5.3. Model reliability

In our model we have simply assumed that erosion is fluvial and proportional to the size of the catchment and the square of the topographic gradient. As such, alluvial channel sedimentation in the washes or short range transport processes (i.e., debris flows or mass diffusion on hillslopes) are not considered. In a desert region like Nevada, fluvial incision models clearly need careful evaluation.

Hillslope processes, typically modelled by mass diffusion (Stüwe, 2007), can easily be excluded as an important process at Yucca Mountain based on the shape of the washes: the topographic profiles shown in Fig. 6 (top) indicate that all gullies that drain east from the principle crest separate relatively sharp ridges. Hillslope processes typically cause rounded crests, separated by V-shaped valleys. The absence of hillslope processes is in fact typical for desert regions: the variation of the Nevada climate over time was considered by Forester et al. (1999). They suggested that Nevada responds to a global climate cycle of some 400,000 years and subcycles of 100,000 years with the next 100,000 years being similar to those between 400,000 and 300,000 years. On a shorter time scale, Forester et al. (1999) report of a series of events that cause fluctuations in erosion rate on a scale of 10,000–50,000 years. These include the influence of glaciations, hill slope stabilisation by vegetation and others. However, the record of sediment cores from the Lake Owens basin appears to indicate a near continuous sediment supply over the last 500,000 years, suggesting a largely constant erosion rate over much of the Quaternary. Currently, there is about 15 cm/year rainfall in this part of Nevada. However, occasional floods do occur, as for example in July 1984 when about 15 cm fell within 2 days (Coe et al., 1997). Bookhagen et al. (2005) showed that most of the fluvial erosion in the Himalaya occurs in abnormal years where the monsoon exceeded its mean precipitation. Similarly, Lavé and Avouac (2001) showed that most of the erosion is controlled by the decadal peak discharge.

Aside from the potential influence of hillslope processes it is, in principle, also possible that the stream power approach itself is inappropriate. A series of other models have been proposed to describe bedrock incision. Kooi and Beaumont (1994) presented already bedrock incision models based on a reaction length scales and the sediment carrying capacity of the river and Whipple (2004) or Wobus et al. (2006) presented a summary of more recent bedrock erosion models, some of which are even tested experimentally (Sklar and Dietrich, 2004). Fortunately, it appears that the stream power approach is robust against many different actual processes acting in bedrock channels (e.g. Stüwe et al., 2008). We only note that several authors agree that the stream power model may break down for catchments smaller than about 5 km^2 in size (e.g. Wobus et al., 2006) and that the smaller gullies may therefore not be well described by our model.

6. Conclusion

We conclude that erosion will denude the Yucca Mountain crest by several hundreds of meters in a time between 500,000 years and 5 my. This estimate is based on minimum assumptions for all parameters, and the time of erosion is therefore a maximum. Importantly, the original thickness of the Rainier Mesa Tuff on top of the Yucca Mountain crest plays a crucial role in calculating a more refined estimate of the total erosion time. We also note that the incision of the surface to the depth of the waste deposits site is a limiting time to acute danger. Long before this, the fractured unit of the Topopah Spring Tuff will have been exposed to the surface, causing potentially substantial alterations of the hydrology of the system. In summary, we conclude that any "Total System Performance Analysis" as has been performed by the U.S. Department of Energy for the site must include erosion as an integral part of its predictions.

Acknowledgements

Stefan Hergarten is thanked for being a continuous source of interesting discussions and assistance with the coding of the model. Mike Thorne and Steve Frishman are thanked for providing early reviews of this manuscript. Two anonymous reviewers are thanked for their constructive comments and Richard Marston for his prompt and rigorous editorial job as well as the elegant handling of the inescapable delays during the review process.

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