Preliminary study on quantitative simulation of Danxia landform evolution under the action of tectonic uplift and running water erosion

Fujun Liu*, Xinmin Li
College of Earth Sciences, East China University of Technology, Nanchang, Jiangxi, China

*Corresponding author: fjliu@ecit.edu.cn

Abstract. To better understand the influence of lithology, climate and tectonic features on landform evolution of Danxiashan, the research simulate complex Earth systems with Channel-Hillslope Integrated Landscape Development (CHILD) which embodies quantitative hypotheses about those systems. The model verifies the correctness of the concept of developmental stages and divides it quantitatively. The infancy, accounting for the entire evolution of 3%, develops large tracts of Continuous surface; the youth period accounts for 4% in which emerge a large number of negative landforms; the adult period accounting for 52% has longest evolution and there are many vertical cliffs; the late period accounts for 34% when hilltop gradually rounds; the decline phase emerges a chain of undulating hills, accounting for 7%. In geomorphology, mathematical and numerical models provide a crucial link between stratum, climate and tectonics.

Keywords: Tectonic uplift, Running water erosion, Danxia landform, Landform Evolution, Quantitative simulation, Channel-Hillslope Integrated Landscape Development

1. Introduction
Davis' theory suggests that landform is a function of structure, action and time. As a famous trinomial in the theory of geomorphic erosion cycle, it is the first time to describe the geomorphic cycle process of land flowing water erosion area in a semi-quantitative way. After that, with the updating of remote sensing, precision measurement, computer and other research methods and the strengthening of mutual penetration among various disciplines, the research on geomorphological evolution gradually moved to a new stage of combining field practice with computer simulation.

In 2010, after "Danxia in China" was officially listed on the World Heritage List, Danxia landform received more and more attention. The research on Danxia landform is deepening, and the research on Danxia landform in China is going to the world. However, for a long time, Chinese scholars' research on Danxia landform mostly focused on qualitative description and inference of morphological characteristics, development conditions and evolution process. On the whole, the study of Danxia landform in China lacks in-depth study of landform expression and landform development process under external dynamic conditions.
The research on geomorphic evolution abroad mainly focuses on various natural processes and environmental factors affecting geomorphic evolution [1, 2, 3, 4]. With the rapid development of society, people's cognitive demand for geological resources is increasing. By quantifying some concepts in the process of landform evolution, the empirical formula or ideal equation of evolution is established, and the evolution process of landform is quantitatively restored. In this paper, taking Danxia Mountain in Guangdong Province as the research object, drawing lessons from the previous research results, and using CHILD Model (Channel-Hill Slope Integrated Landscape Development), the quantitative simulation evolution of Danxia Mountain was preliminarily explored.

2. General situation and research methods of the research area

Under the influence of lithospheric extensional tectonic setting [5], a series of intermountain faulted basins were formed in South China. Danxia Basin is located in Renhua County at the junction of Guangdong, Jiangxi and Hunan provinces. Controlled by Wuchuan Sihui fault zone and Shaoguan-Renhua Fault Zone, it is distributed in NE-trending rhombus. There are few alkaline basalts and bimodal volcanic rocks under the basin, and there are nearly 4000m red beds in Cretaceous. The strata in Danxia Basin are mainly composed of Sandong Formation, Maziping Formation, Changba Formation and Danxia Formation [6]. Danxia Formation can be divided into three sections according to lithological combination, which are mainly a set of conglomerate, glutenite, gravelly sandstone, unequal feldspar Shi Ying sandstone [7], and clastic rock composed of silty mudstone, and "Chibi Danya" Danxia Mountain is developed. Danxia Mountain is the world's "Danxia landform" named place, and the representative of Danxia landform in its late prime, which is typical and suitable for quantitative simulation and exploration of landform evolution.

Irregular grid model (TIN) cuts the spatial area into several grid units, giving readers a clear and intuitive cognition. The displacement of grid represents the change of surface morphology. On the basis of deep understanding of the formation mechanism of Danxia landform, the previous models of landform evolution control equation, sediment erosion, transportation and sedimentation were analyzed, and the simulation was carried out in combination with the stratigraphic characteristics, structural evolution model and climate change analysis in Danxia Mountain area. Through the comprehensive application in CHILD, the parameters are constantly corrected, and finally the results are obtained.

3. Principle of quantitative simulation

3.1. Fundamental principle

In fact, the basic principle of quantitative evolution of Danxia Mountain landform is to restore the change law of elevation of each point on the topographic surface of a specific area with time. In the computer model, the mass continuity equation is used to realize the fluctuation of terrain surface [8].

$$\frac{\partial z}{\partial t} - \nabla q_x + U(x, y, t)$$

In which \(z\) is the elevation of terrain surface, \(t\) is the time of elevation change, \(q_x\) is sediment flux, and \(-\nabla q_x\) represents different transportation and erosion conditions. The Hamiltonian operator can take advantage of its dual character of vector and differential operator, and present different forms according to different assumptions preset in the process of motion. \(U\) is a function of datum change, and its independent variables are the coordinates \((x, y)\) and time \((t)\) of a certain point in the horizontal plane of the region. The finite volume method is used to solve the continuity equation, that is, the spatial three-dimensional surface shape described by the irregular triangulation network (TIN). In this paper, 4000 m ×4000 m is selected as the simulation area, and the whole evolution process is assumed to be 7Ma [9].
3.2. Material base

The red bed is a red continental clastic rock series, which is the material basis of Danxia landform development [10]. The stratum developed in Danxia Mountain is mainly Late Cretaceous Danxia Formation ($K_2d$), which is widely distributed in the higher central part of the basin, with a thickness of about 1000m. The lithology of this group is coarse and well cemented, and Danxia landform is the main feature. According to its lithology, it is divided into three sections from bottom to top, the lower section is Bazhai section, and its lithology is maroon massive conglomerate, glutenite and gravel sandstone, which is in integrated contact with the underlying Changba Formation; The middle section is jinshiyan section, which has large plate-like cross bedding and purple-red thick-layer unequal-grained feldspar sandstone; The upper member is Baizhaiding, which is mainly composed of brownish red conglomerate, glutenite and medium coarse sandstone, and produces Charophytes [11].

The change of grain size is not only an important sign of lithologic stratification, but also a key factor affecting sediment transport, sedimentation and erosion. Wilcock [12] first noticed this, divided sediments into sand and gravel, and successfully established a transport and erosion model with gravel mixture as lithology. At the beginning of this model, the stratum is gravel mixture, in which conglomerate accounts for 70% and sandstone accounts for 30%, so as to restore the lithologic characteristics of Danxia Formation as much as possible.

Erosion ability mainly depends on the shear resistance of the target strata ($\tau_o$):

$$\tau_o = K \left( \frac{Q}{W} \right)^{M_o} S^{N_o}$$

In which $Q$ is the basin area, $W$ is the channel width, $S$ is the channel change gradient, and the rest are the specific parameters of the target rock stratum.

$$D_e = K_{br} \left( \tau_o^{P_b} - \tau_e^{P_b} \right)$$

In which $K_{br}$ is the erosion rate coefficient, $\tau_e$ is the critical value of erosion, and $P_b$ is a specific parameter for different lithology. Erosion occurs when the scouring force exerted on rock exceeds its own resistance.

3.3. External force condition

Climate change is an important reason that affects geomorphic evolution. Precipitation is an important parameter to characterize climate. The evolution of geomorphology is long-term, and the time scale is generally millions of years. However, in reality, precipitation will have obvious changes within hours or even minutes. How to be compatible with continuous geomorphic evolution process and discrete precipitation time is an important issue in the computer simulation of several million years.

At present, the mainstream precipitation models are Bartlett-Lewis model [13] and Poisson model[14]. Bartlett-Lewis model allows a large change of rainfall intensity in a small time interval, but it needs a large number of parameters [15]. Poisson model is concise without loss of generality[16], which is widely used in the research and calculation of surface water balance [17]. In order to restore the function of short-term precipitation better, Poisson model is selected in this paper.

Poisson distribution is a classical probability model describing the distribution of rare events. Poisson model does not list the specific precipitation change records in detail, but adheres to the principle of "constant ratio" and explains the random nature of precipitation in climate and erosion models by amplifying the precipitation change in a single cycle. Compared with ordinary random precipitation model, this method abandons free parameters and emphasizes the statistical analysis of real data, so it has certain physical significance in the current geomorphic evolution model.

The model has three main parameters in a single precipitation cycle, namely, single precipitation intensity ($P$), single precipitation event duration ($T_e$) and interval between two adjacent precipitation
events ($T_b$). The intensity and duration of each precipitation event are relatively independent. The numerical expressions of the three are as follows:

\[ f(P) = \frac{1}{P} \exp\left( -\frac{P}{P} \right) \]

\[ f(T_r) = \frac{1}{T_r} \exp\left( -\frac{T_r}{T_r} \right) \]

\[ f(T_b) = \frac{1}{T_b} \exp\left( -\frac{T_b}{T_b} \right) \]

When the precipitation exceeds the absorption capacity of the surface, it converges into a river and forms runoff. The mud and sand carried by runoff can complete the shaping of surface morphology through the action of river network and structure:

\[ Q = (P - I_c)A \quad P > I_c \]

$I_c$ is the permeability of the earth's surface, including the water absorption capacity of soil and vegetation.

This is also a commonly used runoff generation mechanism. In this simulation, $P=4.09m/a$, $Tr=44a$ and $Tb=56a$ are used for calculation [18].

3.4. Tectonic condition

Tectonic movement is an important factor to form Danxia landform. On the one hand, the red bed rises and suffers from weathering and denudation; on the other hand, it forms joints and breaks rocks, thus reducing the weathering resistance [19]. The structural basis of Danxia landform development is that the internal structure of the basin controls the pattern and even the shape of Danxia mountain block, while the crustal rise and fall controls the process of landform development [10]. Danxia basin is a rhombic faulted basin controlled by a fault zone. Shaoguan-Renhua fault zone cuts the center of Danxia basin and controls the extension and distribution direction of Presbyterian peak, Yangyuanshi, Bazhai and other Danxia mountains, resulting in the overall distribution of Danxia mountains in the northeast direction.

Danxia Mountain is located in the southeast of Danxia landform in China. The Danxia landform types developed in this area are closely related to the relatively stable and slow rise of the crust [20]. Because the crustal activity is not as intense as that in the southwest and northwest regions, more horizontal strata are developed in the later uplift process. In this simulation, the average uplift rate of the crust in Danxia Mountain area is set to be 0.94m/Ma [9], which is processed by cosine, reflecting the intermittence and instability of the actual uplift process.

3.5. Other

The river network density is relatively large, and the meandering deeply shapes the landform, which is also a major feature of Danxia landform in Southeast China. Jinjiang flows through the central basin from north to south and flows into Zhenjiang on the north side of Wuma guicao [21]. In many cases, rivers are regarded as one-dimensional entities. In quantitative simulation, this kind of cognition is often not profound, which largely ignores the role of meandering in widening river channel and side erosion rock mass. According to the geological map, the average drainage area at the river entrance in this area is 16565m$^2$, and the average annual sediment transport capacity calculated by Renhua Hydropower Bureau is 172,300 tons, and the estimated ratio of gravel, sand and mud carried is 10%, 30% and 60% respectively. Lancaster's [22] meandering model defines the forward vector of the river,
which provides convenience for CHILD to realize the migration of the river and directly show the
shaping results of the landform:

\[
\delta = E_0 \left(1 - \frac{P_H h_B}{H + h_B}\right) \tau \hat{n}
\]  

(8)

\(E_0\) is the erosion coefficient of riverbed rock mass, \(\tau\) is the shear stress of riverbed, \(H\) is the water
depth, and \(h_B\) is the height of riverbed deposits above the water surface. \(P_H\) represents the riverbed
erodibility related to the river bank height. \(\hat{n}\) is the vector direction of each grid unit perpendicular to
the downstream of the river.

In addition, in the process of sedimentation and erosion, soil creep, sliding of local faults and other
aspects can be linked with geomorphological evolution.

4. Analog result

4.1. Result analysis

Based on the set evolution rules of stratum, precipitation, structure and other conditions, the evolution
process is simulated by CHILD software in Linux environment. As shown in fig. 1, the visual angle of
the visualization function \(A_{z}=-33\) and \(E_{I}=80\) of the matchable software. By selecting typical mountain
forms in the evolution process, it can be seen that Danxia Mountain has experienced the development
stages of infancy, youth, maturity, old age and decline, which is consistent with the five stages of
Danxia landform development divided by Peng Hua [23].

Fig. 1a shows the simulated initial platform. In order to ensure the realistic environment and visual
effect as much as possible, each point of the platform randomly floats up and down for 5m. At 0.1Ma,
the crust rises, but the top of the mountain remains a continuous plane. At 0.2Ma, the continuous area
of the top surface is still over 60%, because there are obvious grooves in local areas cut down by
running water. According to Peng Hua's [23] classification index of Danxia landform development
stage, 0-0.2Ma is the young stage of Danxia mountain development. At the peak of 0.3Ma, the
continuous surface was further cut, and a large number of negative landforms appeared, which was the
youth. Compared with 0.3Ma, the peak forest is more developed and the ridge is more obvious and
prominent, which is called the prime period. At 5.5Ma, the hills of Danxia Mountain are obvious, and
peak forests are developed locally. At 6.5Ma, it entered the decline period, and no peak forest and
peak cluster developed basically, and a large area of red bed and low hill platform appeared.

With 0.2Ma, 0.3Ma, 4Ma, 5.5Ma and 6.5Ma as time nodes, this simulation has verified the
qualitative Danxia landform development stage to a certain extent. In the whole evolution process, the
duration of infancy, youth and decline is relatively short, accounting for 3%, 4% and 7% of the whole
evolution process respectively. The prime of life lasts the longest, accounting for 52%, which is
mainly related to tectonic uplift.

Figure 1a Initial  

Figure 1b 0.1Ma
Figure 1. Typical simulation results of different periods of Danxiashan

In fig. 2, the angle of view is changed to Az=-31, El=27, and the corresponding time of 2a and 2b is 2Ma and 7Ma, which more intuitively shows the characteristics of mountain in the prime and decline periods. In the prime of life, the red bed basin rises, the erosion is stable, and a large number of peak clusters and peak forest combinations are developed; The landscape in the decline period is typical and unique, with the most significant difference from other periods. Chibi Danya is no longer developed, and the mountain is generally round, and a large number of residual hills are preserved. Compared with the mature period, the overall elevation in the decline period decreased obviously, showing Danxia landform landscape in the early cycle.
4.2. Simulated evaluation

Danxia Mountain is the essence and representative of Danxia landform in the prime of life. It has a history of nearly 7Ma since the accumulation of the red basin. From the simulation results, although the simulation effect is good in the development stage, the accelerated evolution of the model is nearly doubled. In fact, there will be more or less differences between the simulation results and the real situation at any stage in the model, which reflects the ideality of the model. Some unknown influences and other factors also control the evolution process. The negative feedback of vegetation cover, sediment transport and other factors on geomorphic evolution has not been considered, which also reflects the limitations of the model. At the same time, this is also the main direction of the next research. Generally speaking, as a preliminary study of Danxia Mountain landform evolution simulation, this work is basically effective, which reflects the feasibility of numerical simulation and lays a good foundation for future research in this field.

5. Discussion

Compared with the physical model, the computer model has lower cost and better operability. The application of irregular triangulation is a great innovation of this model. The spatial resolution can be dynamically adjusted by adjusting the grid size, and the surface morphology can be reconstructed in real time based on the modification of parameters, presenting the most intuitive visual effect to readers.

In this simulation, the stratum is regarded as gravel mixture. In fact, CHILD can regard the target strata as a group of lithologic sequences with different depth changes and different sediment compositions, which can show a more real material basis of red beds in combination with stratigraphic chronology and internal structural characteristic data. However, the applicability of the selection of representative stratigraphic sections, spatial scales and specific parameters needs further discussion.

The influence of precipitation change rate may be equal to or greater than that of average precipitation. The results of numerical simulation have shown that the higher the precipitation change rate, the faster the erosion rate and the higher the density of drainage network [2]. Bartlett-Lewis model, as an advanced precipitation model at present, has more complex parameters, but its own algorithm shows more accurate precipitation changes than Poisson model. Therefore, the discussion and application of Bartlett-Lewis model is also one of the future efforts.

Although the crustal uplift is processed by rate cosine, the accuracy is still poor. The research data of river terraces, 200,300,400,500,600 m planation planes [9] and thermo luminescence dating of Danxia Mountain is a way to improve its accuracy. It is a good method to divide the uplift evolution history of nearly 7Ma quantitatively by planation plane data. The development of joints controls the mountain shape, which is very important for Danxia landscape evolution. However, at present, no suitable method has been found to combine the distribution of joints, thus affecting the evolution of surface shape. The influence of weathering is not perfect. Fortunately, the model has good compatibility and supports the optimization of the model and the addition of sub-modules. Realizing the deep integration of information technology and geological research has become an effective way to break through the traditional geological research.

Because of the complexity of geological research, the uncertainty of the whole quantitative geomorphological evolution is inherent. Unknown initial link, limited process cognition and ideal equation of motion are unavoidable topics in practical work. It is also a good idea to reverse the evolution time series, take the existing terrain as the initial environment, integrate the process equation, and reverse the reverse evolution of landform. In addition, the actual observation, remote sensing interpretation, electronic probe, sedimentary statistical analysis, rock sample detection and dating data of Danxia landform have basically completed the accumulation of original data, which are valuable resources for quantitative evolution [24, 25, 26, 27, 28].

Figure 2. Simulation results of geomorphic evolution of 2Ma and 7Ma from different perspectives
Understanding the model is very important. Different models of each link have their own physical and mathematical properties. Generally, the model originates from the synthesis, statistics and analysis of a large number of relevant data in the study area, and its applicability to local areas needs to be verified. Updating, perfecting, exploring the evolution equation suitable for this region and gradually reducing the simulation error are the important goals of geomorphic evolution research.

6. Summary
The surface morphology of Danxia Mountain area can be regarded as a quasi-random sequence of strata, climate and structure. According to the evolution process equation, the mountain evolution process can be simulated with reference to the evolution frequency characteristics.

On the basis of setting the initial environment and boundary conditions, the model verifies the correctness of the concept of Danxia landform development stage and divides it quantitatively. Among them, young age accounts for 3%, youth for 4%, mature age for 52%, old age for 34% and decline for 7%. The results have certain guiding significance for the study of Danxia landform.

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