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A 3-D MODEL OF QUATERNARY TERRACE DEVELOPMENT, SIMULATIONS OF TERRACE STRATIGRAPHY AND VALLEY ASYMMETRY: A CASE STUDY FOR THE ALLIER TERRACES (LIMAGNE, FRANCE)

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ABSTRACT

The combined effects of climate and tectonism on general terrace stratigraphy and valley asymmetry during the last half million years in the Allier system (France) are simulated by a 3-D conceptual model (LIMTER). This model allows the formulation and evaluation of long term terrace formation scenarios for the Allier system. Simulation results suggest that terrace stratigraphy in the study area is mainly the result of internal dynamics and climatic change. Local tectonism contributed to the development of unpaired terraces while the general regional uplift played a dominant role in determining terrace formation and preservation in general.

KEY WORDS River terrace formation Modelling Stratigraphy 3-D simulation Allier Climate Uplift

INTRODUCTION

River terraces are a fundamental part of fluvial landscapes. Their existence and formation have been the subject of research for many years because they provide a relative chronology to which other geological, geomorphological or palaeohydrological events can be related (Dawson and Gardiner, 1987). It has always been tempting to link Quaternary terrace chronologies with established chronologies of major Quaternary environmental changes, such as climatic and sea level oscillations, especially when other dating evidence is not available.

The first and well known generalization about the response of fluvial systems in semiarid to subhumid regions to slight shifts in climate was set forth by Huntington (1907, p. 358) and is called 'Huntington's principle' (Fairbridge, 1968; Bloom, 1978). Huntington's principle was established as a general model which many followed in constructing terrace chronologies, whereby glacials are thought to be characterized by aggrading braided rivers and the interglacials by incising meandering rivers.

The other major generalization of a driving force behind terrace formation which is, or was, often applied concerns changes in base level. Such base level changes may be due to sea level changes or epirogenetic movements. In Britain base level changes received much attention and the relative changes in sea level were seen as a major external driving force for river level changes (Mcgregor and Green, 1978). In continental Europe a climatic school dominated which applied base level changes due to tectonism as a second important external variable (Brunnacker and Boenigk, 1983; Texier and Raynal, 1984).

However, a perfect association of terrace depositional phases and incision episodes with climatic phases of certain base levels is rarely possible, or even likely. Terraces are in fact very complex features, resulting partly

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from external factors and partly from the nature of response in the fluvial system itself. Rivers may make terraces without there necessarily being an external change (Schumm, 1977). Often, the general external model breaks down due to a lack of detailed understanding of the processes operating within the fluvial system.

A direct way to gain more insight into the internal dynamics of a fluvial system is by studying its stratigraphy. The terrace sediment properties, deposition conditions and their sequence can give much detailed insight into former conditions within the fluvial system studied. Breaks or facies transitions within the sedimentary record often mark major environmental changes thus indicating possible external forces controlling fluvial dynamics and terrace formation.

In general, it has long been recognized that alluvial sedimentary successions are composed of two main facies groups: one group comprises sandstones and conglomerates and the other group comprises mudstones and siltstones (Bridge and Leeder, 1979). A similar alluvial sediment discrimination was made in fluvial terrace sediments by Texier and Raynal (1984) who correlated coarse sediments to glacial environments and fine sediments to interglacial environments. They are obviously from the climatic school as they also linked the terraces reviewed with major Quarternary climatic cycles.

A simulation of alluvial stratigraphy within one floodplain under strict assumptions (Bridge and Leeder, 1979) showed that the internal dynamics can strongly determine the stratigraphical record. Tectonic movements had a significant influence upon the simulated successions only if a preferred direction of tilting was maintained. From this simulation and the correlations of Texier and Raynal (1984) it becomes obvious that if one wants to create a more realistic model of fluvial terrace formation, including both internal and external dynamics, one has to incorporate the stratigraphical record.

The advantage of considering both geographical position of terraces and their stratigraphical record is that more effects of changes in fluvial dynamics can be viewed. The role of tectonism seemed only minor in the stratigraphical model of Bridge and Leeder (1979) but when similar movements are considered in a model including terrace formation, more distinct results can be expected. Tectonic uplift is likely to cause vertical erosion of a river and thus abandoning of the floodplain, an effect not incorporated in their stratigraphical model.

In respect to tectonism, river terraces are more valuable than stratigraphy because they give direct indications of former river gradients, and successive terraces show successive river positions. In areas of tectonic activity, valleys and their terraces may be asymmetrical, tilted or warped in various ways, giving valuable clues for the interpretation of tectonic movements.

Models which describe fluvial system dynamics for longer timespans are sparse because most knowledge on fluvial systems is based on short term, well controlled experiments (Gregory, 1983; Dawson and Gardiner, 1987). They are therefore usually based on the correlation of terraces with known major changes during the Quaternary, such as the climate dynamics. Most of these models are used for the interpretation of large terrace sequences.

Recently a quantitative but still conceptual, long term (2 million years) macro-scale (100 km^2) fluvial system model was constructed which simulates the development of fluvial terraces as the result of external and internal changes in the simulated fluvial system (Veldkamp and Vermeulen, 1989). This so-called coarse scale model (Thornes, 1987) only simulated the formation of terraces and did not consider the effects on the fluvial stratigraphical record.

In this paper an attempt is made to analyse and combine the effects of climatic change, tectonism and internal fluvial dynamics on alluvial stratigraphy and valley morphology using a comprehensive version of the existing 3-D fluvial terrace formation simulation model.

As an exercise, a plausible terrace development scenario is simulated for a real fluvial system. This system is the Allier (Massif Central, France) which is chosen because of its large data-base and the 3-D model already developed for this system.

STUDY AREA

The *Allier*, a major Loire tributary, drains the sedimentary Limagne graben and the surrounding crystalline Massif Central in France (Figure 1). Except for these sedimentary and basement terrains, the large volcanic

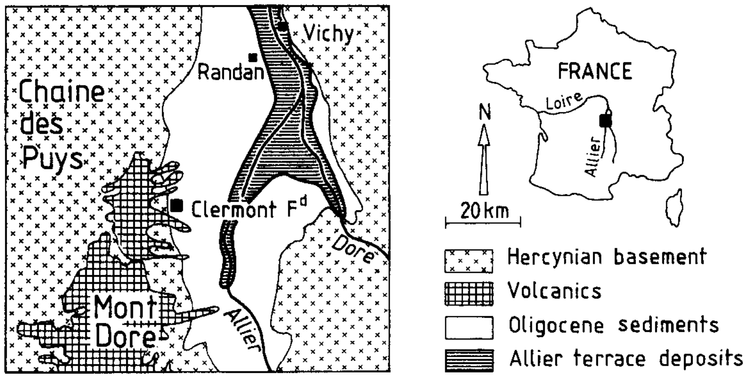

Figure 1. Location of the study area. The Allier basin is situated in the Limagne rift valley in the French Central Massif

bodies of the Cantal and the Mont Dore are also found within the Allier basin. This varied lithology is clearly reflected by the Allier sediments. Further details on the local geology of the Massif Central are given by Autran and Peterlongo (1980).

FLUVIAL TERRACE FORMATION IN THE ALLIER BASIN

One of the most complete terrace sequences in the Allier basin is found near Randan (Clozier *et al.*, 1980). This chronosequence displays at least 10 terrace levels, shown schematically in the cross section of Figure 2. The oldest terrace level in this sequence, fT, is thought to be about 2 million years old (Pastre, 1987). The oldest more certain age is known from pumice fragments in fV_a terrace sediments, indicating an age of approximately 800 ky (Veldkamp and Jongmans, 1990). The younger terrace levels (fV_b, fW_a and fW_b) are unfortunately not exactly dated; fW_a is thought to be approximately 300 ky old. The ages of the youngest terrace are known to range from Late Weichselian to recent times (Raynal, 1984; Kroonenberg *et al.*, 1989; Veldkamp, 1991).

The typical sequence of terraces present in the Allier valley shows that accumulation and vertical erosion alternated repeatedly during general valley deepening. Very similar terrace sequences are found along the Rhine, Meuse and Thames (Van den Berg, 1989; Van Straaten, 1946; Brunnacker and Boenigk, 1983; Andres, 1989; McGregor and Green, 1978).

Most terraces are predominantly gravelly on top with the more sandy sediments dominating in the lower stratigraphical units. This rather uniform stratigraphy made Texier and Raynal (1984) conclude that the Allier terrace stratigraphy displays evidence of Quaternary climatic cyclicity.

The contribution of tectonism to terrace formation in the Allier basin is less obvious than the role of climate. Throughout the Quaternary the tendency towards valley deepening predominated in the entire Allier basin. The total amount of valley deepening at Randan since the Quaternary and consequently the probable total amount of uplift is about 150 m. The actual known tectonic process is gradual neotectonic uplift (Giot *et al.*, 1978). The past tectonic movements in the study area are less well known but the Randan terrace sequence suggests by its asymmetry (Figure 2) an unequal uplift of the valley sides or regional tilting. Since the Randan terrace sequence is situated in a rift valley with active faulting during the Quaternary, unequal uplift rates of both valley sides seems most probable (Larue, 1979; Giot *et al.*, 1978).

In general, only climate and tectonism have been able to steer terrace formation in the Allier basin. Some Allier dynamics related to climate and tectonism in the Allier system are relatively well known, but their combined effect and the exact role of tectonism are still unknown. The 3-D LIMTER (LIMagne TERraces) model is used here to reconstruct the morphology and stratigraphy of the terrace sequence near Randan.

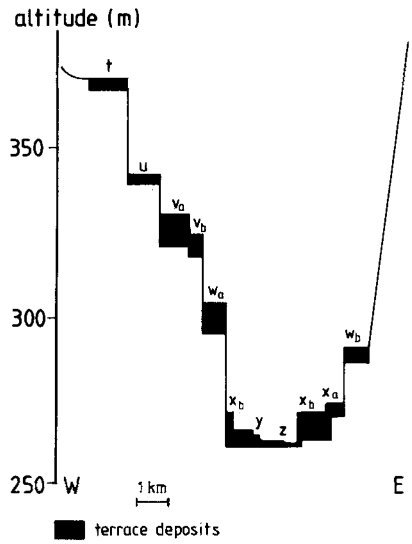

Figure 2. Schematic cross section of the Randan terrace sequence. This section from the oldest Quaternary terrace (t) down to the actual floodplain (z) is the most complete Allier terrace sequence

MODEL CHARACTERISTICS

Model construction, organization and operation have been described in a previous paper (Veldkamp and Vermeulen, 1989). Model organization was done with entities and attributes. An entity is an independent unit in the object system: the entities in this model are LANDSCAPE and RIVER. An attribute is a property, mark or characteristic of an entity, such as discharge for RIVER and valley depth for LANDSCAPE. The attributes have been constrained to lie in realistic domains for the Allier system. The LIMTER entities and their attributes are described in Table I. The interaction between the two entities are defined as erosion and sedimentation processes acting in timesteps of 1000 years.

Table I. LIMTER entities and attributes

A. Time	$1 < \text{time} < 800$ (ky)
B. Entities	
1. Entity: RIVER Attributes	Domain
1.1 Discharge	$1{\cdot}58 \times 10^{12} < \text{discharge} < 9{\cdot}47 \times 10^{12}$ ($m^3\,ky^{-1}$)
1.2 Input load	$0 < \text{input load} < 9{\cdot}46 \times 10^{7}$ ($m^3\,ky^{-1}$)
1.3 Form	Meandering or braided
1.3.1 Width	$0{\cdot}15 < \text{flood plain width} < 14{\cdot}4$ (km)
1.3.2 Max. load	$2{\cdot}22 \times 10^{6} < \text{max. load} < 1{\cdot}10 \times 10^{8}$ ($m^3\,ky^{-1}$)
1.4 Erosion	$-6{\cdot}62 \times 10^{7} < \text{erosion} < 1{\cdot}10 \times 10^{8}$ ($m^3\,ky^{-1}$)
2. Entity: LANDSCAPE Attributes	Domain
2.1 Quplift.	$0 < \text{Quplift} < 0{\cdot}4$ ($m\,ky^{-1}$)
2.2 Quplift–unequal	$0 < \text{Quplift–unequal} < 0{\cdot}05$ ($m\,ky^{-1}$)
2.3 Relief x, y, z	$150 < x < 15\,000$ (m)
	$150 < y < 15\,000$ (m)
	$1 < z < 500$ (m)
2.3.1 Valley depth	$20 < \text{valley depth} < 500$ (m)
2.3.2 Stratigraphy	$0 < \text{stratigraphy} < 1000$ (ky)
2.3.3 Sediment composition	$1 < \text{sediment composition} \leqslant 4$
2.4 Valley width	$0{\cdot}15 < \text{valley width} < 14{\cdot}30$ (km)

These model processes are long term and large scale analogies of real erosion and sedimentation processes. They are artificially constructed processes reacting to changes in the 1000 years discharge/sediment load equilibrium which are both defined as a function of climate. When the sediment input load exceeds the sediment transport capacity, which is a function of discharge, the difference is deposited (NOT EROSION = true), and in case the transport capacity exceeds the input load the difference is eroded in the simulated system (EROSION = true). The main disadvantage of this approach is that the defined processes are not based on any actual system process as in the clastic sedimentation model of Tetzlaff and Harbaugh (1989). Their hydraulically based approach is based on a different scale to our model. We also scaled discharge and sediment load as the resulting processes, while their model calculates actual short term discharges and sediment loads to determine the long term effects of erosion and sedimentation processes. They coped with longer timespans by the compute-and-drift and the compute-and-stop strategies. LIMTER calculations are followed by state determinations and boundary calculations within which LANDSCAPE changes must take place. The LANDSCAPE is changed by modifying grid cell elevations in response to the acting process. The changed LANDSCAPE is stored in a geographical information system (GIS).

The processes acting in the LANDSCAPE are determined by decision rules extracted from general literature on hydrology (Schumm, 1977). These decision rules are:

IF EROSION AND UPLIFT AND MEANDER	THEN INCISION
IF EROSION AND UPLIFT AND BRAIDED	THEN INCISION AND BANK EROSION
IF EROSION AND NOT UPLIFT AND MEANDER	THEN INCISION AND BANK EROSION
IF EROSION AND NOT UPLIFT AND BRAIDED	THEN BANK EROSION
IF NOT EROSION	THEN DEPOSITION
	(disregarding all other conditions)

UPLIFT and NOT UPLIFT are system states indicating the impact of tectonic uplift. UPLIFT is true (NOT UPLIFT = false) when the fluvial erosion is not able to compensate the LANDSCAPE uplift. MEANDER is true when the Allier is meandering while the BRAIDED state is true when the Allier is braiding. The impact of INCISION, BANK EROSION and DEPOSITION in a cross section are shown in Figure 3. Erosion processes are migrating headward along the longitudinal profile, while sedimentation migrates in a downstream direction. Irregular headward erosion during erosion of a meandering RIVER is caused by changes in the effective floodplain width during the simulation. The resulting irregular bank erosion has a similar effect as a meandering river has in a real system.

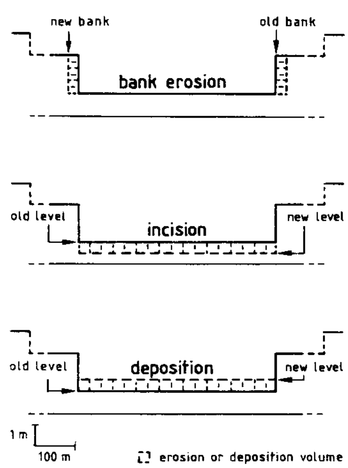

Figure 3. Cross section showing the impact of the model processes: incision, bank erosion and deposition

Terrace stratigraphy

Terrace stratigraphy was also incorporated within the LIMTER model. During the simulations the stratigraphy of the upper 10 m (grid cells) are stored. When sediments are deposited their relative age and composition are stored. Relative age is indicated by the timestep during which sedimentation took place while sediment composition is indicated by a composition class. These composition classes are derived from bulk geochemical sediment research of the Allier terraces. There are four sediment composition classes with the following characteristics:

Class 0: the underlying bedrock;
Class 1: sandy and clayey sediments with a low volcanic content which are deposited during interglacial periods in a meandering system;
Class 2: predominantly sandy sediments with an intermediate volcanic content which are deposited in a braided system during glacial periods;
Class 3: gravelly sediments with a high volcanic content which are deposited in a braided system at the end of a prolonged glacial period (> 10 ky).

MODEL INPUT

The inputs and outputs of the Allier system simulations are described after which simulation results are presented and discussed.

Climate

The Quaternary has known many astronomically controlled mondial changes in climate, which can be very satisfactorily described by Milankovics' curve (Berger, 1978). These climatic changes are well registered in deep sea cores, ice cores and loess profiles giving indications of the relative amounts of water stored in ice masses, and changes in air circulation. Although the relationship between fluvial dynamics and climate behaviour depends on the nature of climatic change and the effects of such changes on discharge and sediment load (Lowe and Walker, 1984), a simple linear relation was assumed between caloric insolation (Berger, 1978), mean 1000 year discharge and 1000 year sediment load each 1000 years. During glacials, much water is stored in glaciers and drier continental climates prevail causing lower mean 1000 year discharges in rivers. Due to the drier and colder glacial environment the vegetation cover decreases causing an increase in sediment supply to fluvial systems. Interglacials yield the opposite picture: an increase in the mean 1000 year discharge and a complementary decrease in the 1000 year sediment supply. This simplified relationship between climatic change and mean discharge and mean sediment load changes is partly supported by changes in magnetic susceptibility as found in thick loess sections in China, indicating dry glacials and wet interglacials during the last 2·4 million years in this continental area (Heller and Wang, 1991). We expect that a similar condition prevailed in the Allier basin where the glacials were dry due to a permanent high pressure area at the glaciers.

As model simulations require a climatic input with a constant reliability during the simulated time span, a simplified Milankovics' curve was used as the basic climatic input. The effects of climatic dynamics are simulated as changes in 1000 year discharge and 1000 year sediment load in the Allier. Mean discharge each 1000 years is simulated as the sum of three SIN functions with the periodicities of the precession (23000 years), obliquity (41000 years) and eccentricity (96000 years). As the sediment load is assumed to have a similar cyclic behaviour as the 1000 year discharge, but out of phase, it was simulated as the sum of COS functions with the same three periodicities. Although these curves do not exactly match the climatic curves derived from deep sea cores and loess sediments, they sufficiently describe climatic changes during the Quaternary for our conceptual long term modelling purposes.

Except for the difference in behaviour of the fluvial dynamics in glacial and interglacial stadia, the transition from a glacial to an interglacial environment was also taken into account. Bulk sedimentary research in the Allier basin showed that changes in sediment flux magnitude and sediment composition are related to the intensity and duration of a climatic episode (Veldkamp, 1991). During prolonged glacials, large glaciers were built up on the higher parts in the Allier basin, the Cantal and the Mont Dore volcanoes (Veyret, 1978). When climatic conditions improved, relatively fast glacier melting caused the release of large quantities of coarse volcanic-rich sediments into the Allier.

Fluvial dynamics related to glacier melting are incorporated within the LIMTER model as follows: when a glacial lasts longer than 10 ky an extra large sediment flux (four times normal flux) with composition class 3, is released into the system at the transition to a new interglacial period. The magnitude of an extra sediment flux of four times a normal flux is derived from the average of reconstructed Weichselian fluxes in the Allier which range from two to almost 10 times the interglacial flux quantities (Veldkamp, 1991).

The resulting alternating erosion and deposition states during the simulation are clearly illustrated by the cumulative erosion graph (Figure 4). The oscillating curve is a function of Milankovics' curve, the negative peaks are the extra sediment fluxes at the glacial/interglacial transitions causing sedimentation (negative erosion) in the Allier system.

Tectonism

Two different components of tectonism (Figure 5) are incorporated in the LIMTER model. A component of gradual uplift of the whole simulated landscape (QUPLIFT), and an uplift component describing the difference in uplift rate of the landscapes on both sides of the Allier (QUPLIFT–UNEQUAL). The latter tectonic component assumes an active fault in the middle of the Allier valley, dividing the entity LANDSCAPE into two equal parts with different uplift rates. There is some field evidence suggesting the presence of such a faulting zone.

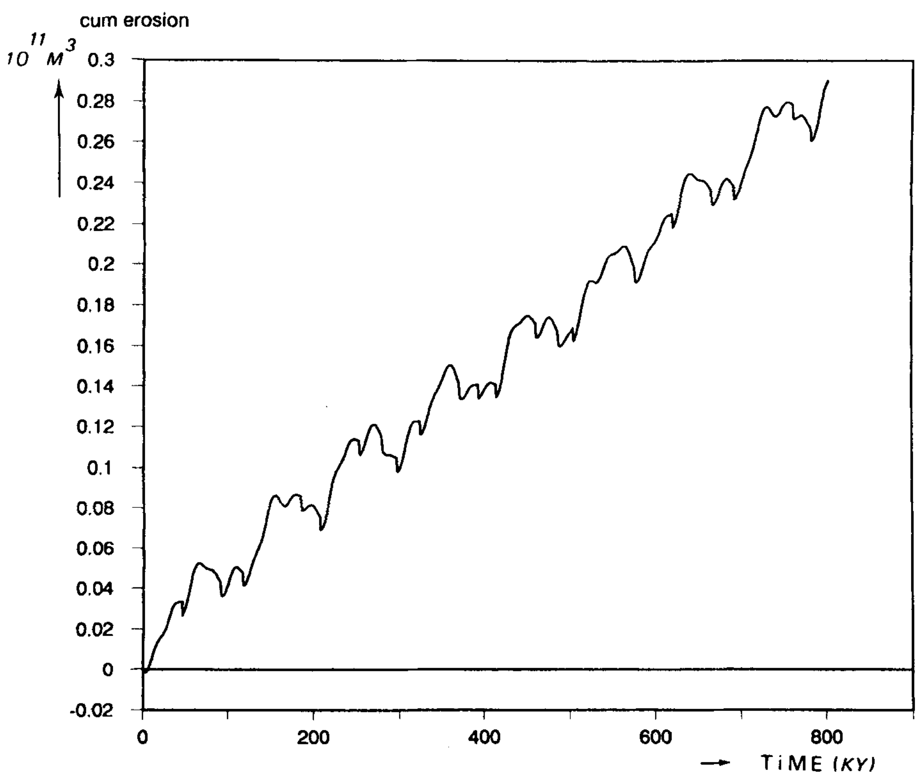

Figure 4. Cumulative erosion curve, derived from changes in discharge/sediment load equilibrium during simulation of LIMTER. This curve illustrates the alternating erosion and sedimentation stages during simulations

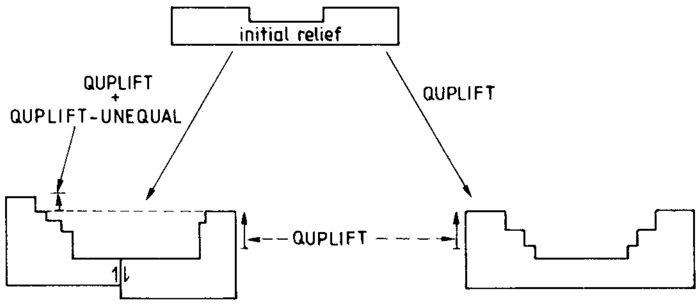

Figure 5. Two tectonic components as input of the LIMTER simulation. QUPLIFT is the general uplift of the modelled area, QUPLIFT–UNEQUAL is the difference in uplift rate between the two valley sides, assuming an active fault in the middle of the valley parallel to the flow direction

Because there is no proof that tectonism has known changing rates in the Allier basin in time, only simulations with constant gradual uplift are made.

Initial relief

The initial relief (Figure 6a) is also a model input. The simulated LANDSCAPE has a surface of 225 km^2 (15×15 km), a maximum altitude of 270 m and a minimum altitude of 240 m. The initial relief consists of a broad (valley width = 7800 m), shallow (valley depth = 30 m) valley. Terrace stratigraphy displays only age 0 and composition class 0 indicating that no fluvial sediments occur in the initial LANDSCAPE.

MODEL OUTPUT

The output of the LIMTER model is a huge data file (GIS) with the LANDSCAPE altitudes and stratigraphy for each timestep. With these data, cross sections, maps, 3-D relief graphs, or 3-D graphs of one cross section development in time can be drawn.

MODEL TUNING

Model tuning was done with the mean 1000 year discharge and 1000 year sediment load and their amplitudes. Two known system conditions were used as reference during tuning activities: the total net volume eroded during the Quaternary, and the fact that alternating erosion and sedimentation have taken place.

SIMULATION RESULTS

A simulation with plausible realistic simulation results is presented in more detail. This simulation had the climatic inputs as described by the model input, QUPLIFT of 0.1 m ky^{-1} and a QUPLIFT–UNEQUAL of 0·01 m ky^{-1}. The LANDSCAPE development in time during this simulation is illustrated in 3-D form in Figure 6 for each 100 ky.

Valley morphology

Simulations without tectonic uplift result in temporary terraces only, while large constant uplift rates ($> 0{\cdot}3$ m ky^{-1}) cause steep canyons without terraces, and uplift rates of around 0·1 m ky^{-1} display many terraces. Simulations with gradual uplift of the LANDSCAPE as a whole result in paired terraces only. When a difference in uplift rate for both halves of the LANDSCAPE is introduced (QUPLIFT–UNEQUAL > 0), asymmetrical terrace sequences develop with both paired and unpaired terraces. Most terraces remain on the

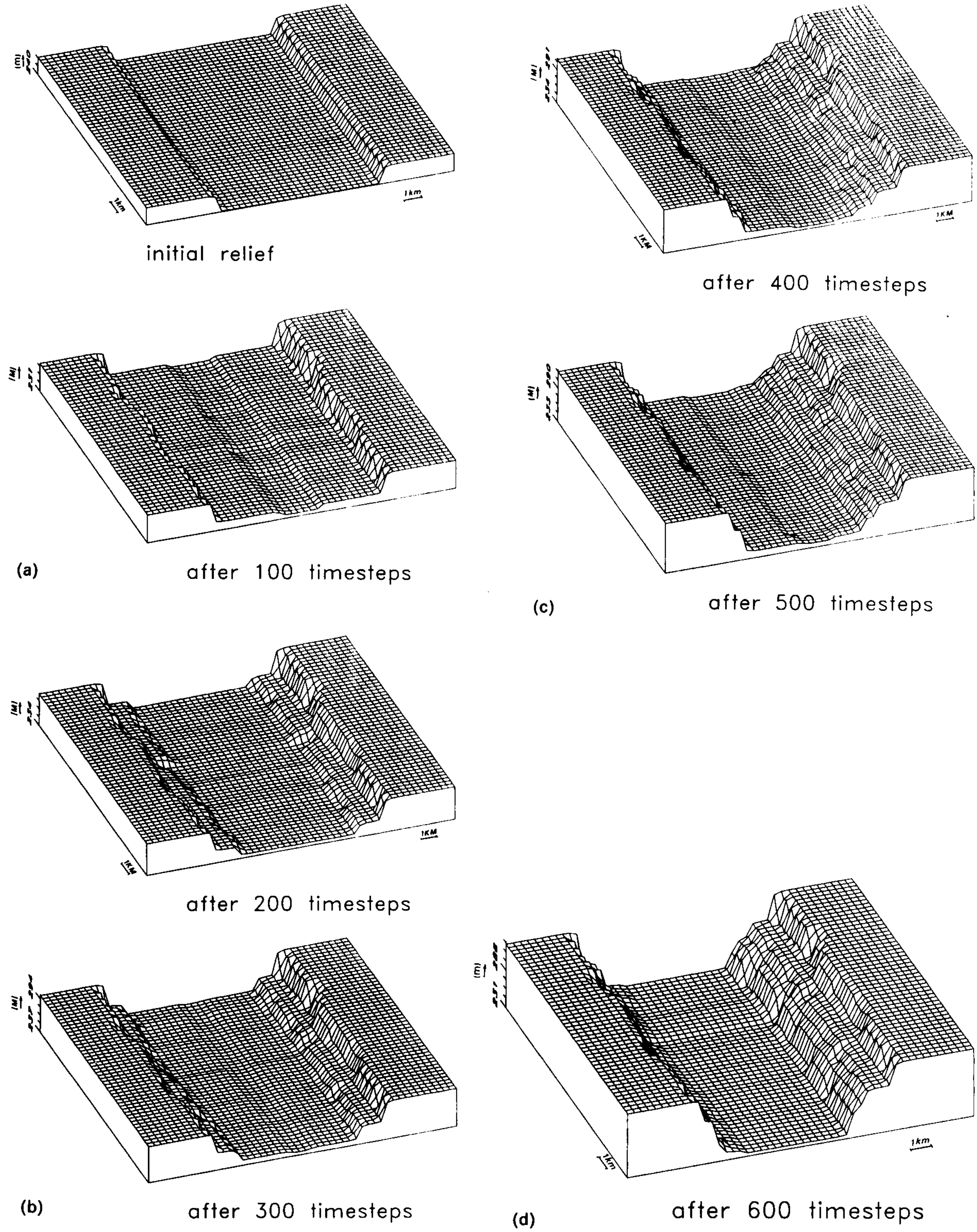

Figure 6. 3-D valley relief development during simulation, in timesteps of 100 ky. The effects of changing fluvial dynamics are illustrated by incision and terrace formation. Irregularities in the valley slopes are also caused by changes in fluvial dynamics during the headward erosion

valley side with the highest uplift rate. Simulations with both general and unequal uplift components result in landscapes with characteristics comparable to the present Randan terrace sequence. To illustrate the incision and sedimentation dynamics in more detail a cross section sequence in time is drawn in Figure 7, showing relief changes during the first 350 ky of the simulation. Both figures clearly show the alternating incision and sedimentation of the Allier in time causing several different terrace levels. The effects of unequal uplift also become clear during the simulation: an asymmetrical terrace sequence develops as a result of distorted downgrading of the Allier system.

An interesting simulation result is the development of unpaired terraces due to changes in an external factor: unequal uplift. This result contrasts with the traditional view that unpaired terraces are generated by changes in internal factors such as a widely swinging meander belt which produces unpaired terraces during the slow lowering of a broad floodplain.

Terrace stratigraphy

Terrace stratigraphy displays the total effect of both sedimentation and erosion processes related to the sediment flux dynamics during simulation. Simulations without major changes in sediment fluxes due to climatic changes result in relatively thin sediment layers with a very simple stratigraphy. When the sediment composition and flux magnitude are related to climatic environment a very complex terrace stratigraphy develops. It is not surprising that the largest sediment fluxes (class 3), i.e. those related to glacier melting, are relatively well preserved in the terrace stratigraphy. During these large fluvioglacial sediment fluxes the floodplain and the lowest terraces are buried by these sediments. This burial causes the formation of the 'standard' Allier terrace stratigraphy with relatively volcanic-poor sandy units buried by volcanic-rich gravelly units. This development can be seen in the cross sections in Figure 8, displaying the changes in both relief and stratigraphy (sediment age and composition). Six cross sections are given as an illustration of fluvial system dynamics during the last simulated 100 ky shown each 20 ky. The last cross section shows the LANDSCAPE during an interglacial period like the present Allier and can therefore be directly compared with the actual Randan cross section.

Although the simulated river exhibits a meandering state many times, it is surprising that the typical interglacial sediments (class 1) are rarely found in the stratigraphical record. This limited occurrence of meandering sediments is true for both the described simulation and the actual Randan terrace sequence. During LIMTER simulations interglacial sediments are deposited during each interglacial but they are almost always eroded during the same interglacial or the subsequent glacial. The limited occurrence of interglacial sediments in the sedimentary records seems to be due to the mainly eroding characteristics of a meandering Allier, the most common interglacial Allier state.

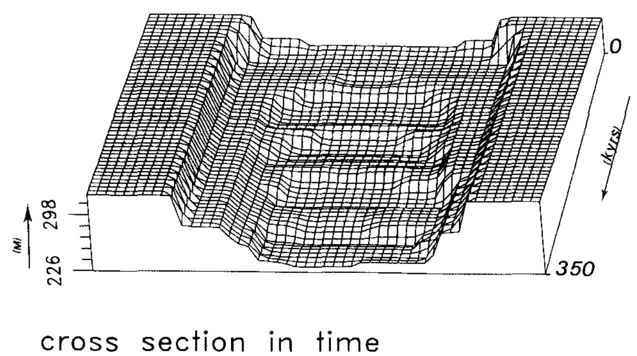

Figure 7. 3-D graph of the development of one cross section in time. An asymmetrical terrace sequence develops as a result of distorted downgrading of the Allier system

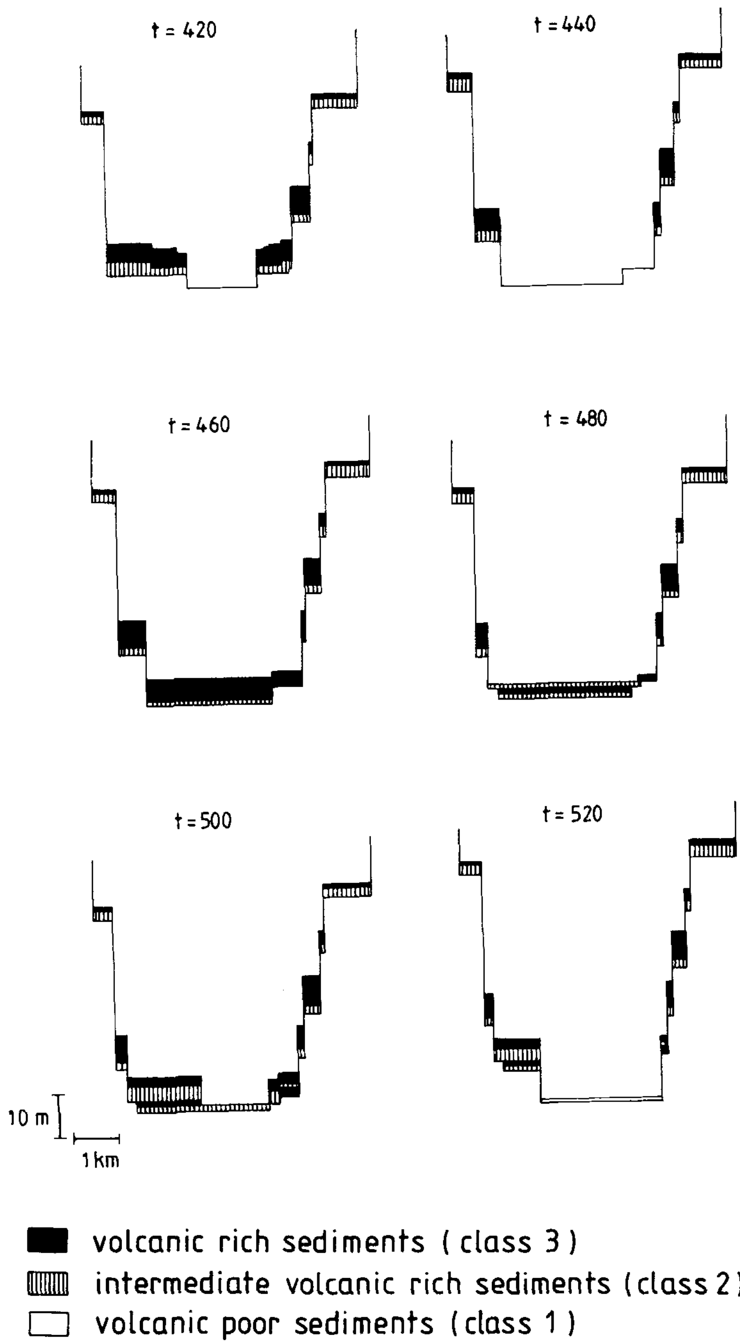

Figure 8. Cross section ånd terrace stratigraphy development during the last 100 ky of the simulation shown each 20 ky

EVAULATION OF THE SIMULATED RANDAN TERRACE SEQUENCE

In Figure 9 the cross section after 520 timesteps (ky) is plotted together with the cross section near Randan, allowing comparison of the LIMTER simulation results with the actual Allier system at Randan. It has to be realized that the Randan cross section in Figure 9 is only a highly schematic version of reality. The effects of

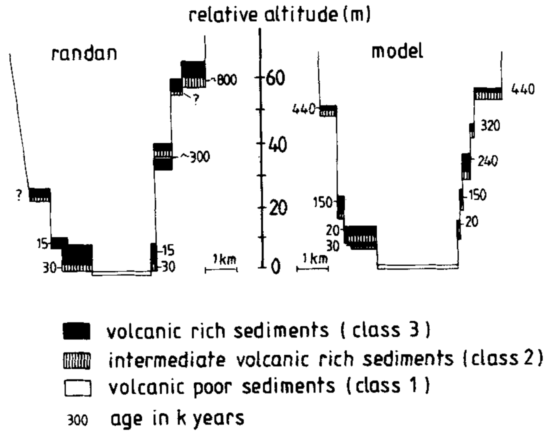

Figure 9. Comparison of the Randan terrace sequence and the model output. Note the good correspondence between model and reality for the younger terraces

mass movements on slopes and the dissection of terraces by minor tributaries are not included in the schematic cross section. Because LIMTER has only conceptual value the correspondence between the model and the Randan sequence should be reviewed qualitatively only.

The major points of correspondence between LIMTER output and the Randan sequence are the number of terraces, the general terrace stratigraphy and the relative altitudes and distribution of the terraces on the valley slopes.

There are also clear differences between the model output and the Randan sequence. In LIMTER a relative age of 420 ky is found for the 65 m terrace (V_a) while in reality this terrace level is thought to have an age of approximately 800 ky. This large age difference suggests that the incision rate in the LIMTER model was probably too fast compared with what actually took place in the Allier system. On the other hand, the age difference between the younger terraces in the model and in the Allier is much smaller, suggesting a much better simulation of the Allier system during the last few hundred thousand years. This discrepancy in age correspondence between simulation results and reality suggests that the uplift rates near Randan changed during the Quaternary. There seems to have been almost no uplift between 800 and 400 ky BP. This interpretation implies that the model assumption of constant uplift rates is incorrect for the simulated Randan terrace sequence. A change in tectonic activity is supported by some distorted longitudinal terrace profiles indicating regional tectonic activity between the formation of the V and W terrace levels (Larue, 1979; Giot *et al.*, 1978).

Another striking difference between simulation results and reality is the complete lack of terrace remnants of the V_a and V_b terraces on the eastern valley side in the Randan sequence. This discrepancy remains difficult to interpret but it might be related to the same tectonic events which caused the differences in terrace sediment age.

In general it is striking that relatively simple model inputs can accomplish such a complicated terrace sequence, including unpaired terrace levels and a relatively complicated terrace stratigraphy. Despite the differences between the LIMTER output and the Allier terrace sequence, the simulation is thought to display a possible general scenario for the development of the actual Randan terrace sequence.

GENERAL APPLICATIONS OF LIMTER

LIMTER has of course no validity outside the Allier basin because it was adapted to this unique system only. The impact of climate was relatively straightforward to simulate by changes in the 1000 year sediment and discharge, because the Allier system is known to be strongly controlled by fluvioglacial fluxes from glaciers in its headwaters. It therefore remains to be seen whether this input assumption has any validity in a system without such a fluvioglacial control during the Quaternary.

The hydraulically based clastic sedimentation model of Tetzlaff and Harbaugh (1989) seems to allow a more straightforward interpretation of simulation results than LIMTER. LIMTER calculates only an average impact for each timestep (1000 years) while they coped with longer timespans by the compute-and-drift and the compute-and-stop strategies. Although Tetzlaff and Harbaugh's basic assumptions seem realistic, their complete numerical model has so many calculation operations that no reliable long term results may be expected. During each operation the calculation errors increase resulting in unreliable outputs. LIMTER has less realistic basic assumptions but has much fewer calculation operations, reducing the calculation errors and limiting the computing power demands. It is obvious that both approaches have different advantages and disadvantages and are, more or less complementary.

It is beyond any doubt that an elaborate model with a solid hydraulically based foundation, such as that constructed by Tetzlaff and Harbaugh (1989), will suggest a more generally validity. But such a numerical model is mainly focused on transport and deposition processes derived from sediment characteristics, neglecting other complex dynamics in the fluvial system affecting the morphology as well. The remaining problem is that such a model should be tuned to both sedimentary sequences and valley morphology (river terraces). The latter is the main goal of LIMTER while long term hydrologically based models can only be tuned to sedimentary sequences. Another problem is to obtain a reliable long term input for such a hydrological model, because our over-simplified input assumption is unsuitable for such a model.

CONCLUSIONS

The long term simulations of an Allier-like system with LIMTER suggest that the Allier terraces at Randan are mainly the result of internal dynamics responding to both climatic and tectonic factors. The conceptual LIMTER model illustrates that in the Allier system tectonism may have played a dominant role in determining the terrace formation and preservation, while climatic dynamics seem to have strongly determined terrace stratigraphy by causing changes in composition and magnitude of sediment fluxes.

Valley morphology seems to be the result of the interaction of tectonic movements and fluvial dynamics. The effects of unequal uplift are unpaired terraces and asymmetrical downgrading of the simulated river.

Our modelling exercise shows that rather complex fluvial systems can be simulated satisfactorily using simplified and descriptive knowledge of fluvial systems only.

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