Master of Science thesis report

Quaternary longitudinal profile development of the Miño-Sil river system, NW Iberia

The interplay between neotectonics, sea level and climate change

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Photograph front cover: Strongly weathered Miño terrace under eucalyptus forest, Galicia.

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Summary

The longitudinal profile development of the NW Iberian Miño-Sil river system was investigated by means of field work and numerical modelling techniques.
Field work was carried out in the lower reach of the Miño river in order to 1) determine the number of alluvial terraces present; 2) to investigate if there were ongoing differential tectonics between both sides of the river and 3) to collect samples for OSL-dating.
In total ten terrace levels were distinguished and fifteen samples for various terrace levels were collected. No differential tectonics between both sides of the Miño were discovered. Due to saturation of the OSL-signal, minimum age estimations for the older terraces were established at 100-200 ka.
The longitudinal profile development of the Miño-Sil system was investigated by means of the numerical model Fluver 2. The modelled time-span was set at 800 ka and calculations were made every twenty years in steps of 340 m along the profile. Model input comprised an initial longitudinal profile, sea level changes, climate-controlled discharge dynamics and tectonic uplift in the form of differential block movement. Due to the absence of information on tectonic block movements, several scenarios were developed by inferring uplift rates from fluvial terrace sequences and linking terrace aggradation to either glacials or interglacials. One scenario used a marine terrace sequence instead of a fluvial sequence.

Model outcomes showed that terrace formation in the lower reach of the Miño was dominated by eustacy and driven by tectonic uplift. Terrace build-up started at the onset of interglacials in the form of a delta near the Atlantic Ocean. From here on, sediments migrated almost 130 km upstream in the shape of a backfilling sedimentary wedge. Upstream migration took up over 100 ka, suggesting that during periods of low sea level which caused incision of the wedge close to the coast, aggradation upstream continued. It is not clear as to what extent this time-lag is the result of an incorrectly modelled submarine river profile. Upstream of the sedimentary wedge, eustatic changes triggered continuous incision phases of changing intensity. This implied that the different reaches of the Miño are out of phase and that eustatic changes control fluvial dynamics far upstream. These findings confirm earlier work by Merritts et al. (1994), Tebbens et al. (2000) and Veldkamp & Tebbens (2001).
In the upper reaches of the Sil, ongoing incision took place in a rhythmic pattern following the eccentricity-forced 100 ka climate cycles. These rhythmic incision phases were related to climate-controlled discharges whereby interglacials yielded higher discharges than glacials. This is partly due to model input whereby a linear transformation was made from increased discharges to increased sediment fluxes. In the middle reach of the Miño-Sil, climate control diminishes. These findings contradict existing evidence suggesting that in the hinterland of fluvial systems, fluvial terraces register glacial aggradation and interglacial incision (e.g. Van den Berg, 1996; Starkel 2003). It is suggested that the absence of glacial overland flow and slope processes as model input cause this disparity.
Reconstructed uplift rates and uplift behaviour of the Miño-Sil system agree with those of other fluvial systems in the Northeast Atlantic region. This suggests a globally applicable pattern in uplift behaviour.

Preface

My first encounter with Spain took place in 2002 when I organised an EU-funded student exchange. It happened on chance: I was not particularly interested in Spain because of its brash image of the *Costa's*, but absence of other partners led me to organise an exchange with students from Madrid. I studied forestry at that time and during my ten-day stay in various places in central Spain, notably Segovia, the Extremaduran natural park of Monfragüe and various mountain hamlets my view altered completely. I fell in love with this harsh and yet stunningly beautiful country. Since then I kept returning to the *Kingdoms of Spain*. A practical four-week soil mapping and land evaluation exercise in Andalusia in 2004 was followed by a two-week field excursion and six-week travel period in 2005. During this field excursion, Peter Buurman told me about Galicia and my interest was immediately kindled. This led to me to do my five-month internship in Santiago de Compostela in 2006 with Antonio Martinez Cortizas. This was also the period that I learned to speak Spanish and that I met Ramon Blanco Chao. After my stay in Galicia, I went back to Andalusia to work three months as a scuba diving guide for tourists in Nerja. During this period and the subsequent autumn back in the Netherlands the idea for this thesis was born. Jeroen Schoorl agreed upon supervising me but only on the condition that I would work independently. Not long afterwards, I set off once more with my camper van to Galicia.

I cannot imagine a more satisfying way of doing an MSc thesis as I did. I had the freedom to pursue my own ideas and do it the way I wanted to do it. I did my fieldwork completely independent, using my camper van for driving around and camping. It was very hard sometimes and I often felt lonely. Nevertheless, the discovery of new fluvial terraces, beautiful enclosures and the knowledge that I was doing something new kept me going. The smell of eucalyptus trees, the stray dog that kept me company for two days and the quietness at night while drinking my whiskey along the Miño's riverbank will be etched in my mind forever.

Another personal victory is the language. In January 2006, I did not speak or understand a single word of Spanish. Now, february 2008, I have read a vast amount of Spanish scientific literature and have even taught myself to read Portuguese.

The last thing I would like to mention is the cooperation with the people in Galicia and Portugal. The absence of a hierarchy mentality, their easy association with other people and the notion that there is more in life than work alone made my stay indeed a pleasant one. I greatly enjoyed the company, help and discussions I had with Ramon Blanco Chao and Marcos Valcarcel Diaz in Santiago. In Portugal Maria Assunção Araujo was a great help in providing me with digitised geological and topographical maps and aerial photographs, even though she had the flu and it would have been wiser for her to stay in bed. An initial inquiry from my side for some information led to a cooperation with the people from the geology section of the University of A Coruña. I value the cooperation with Juan Ramon Vidal Romani, Daniel Fernandez Mosquera and Jorge Sanjurjo Sanchez both in the field and in the laboratory. I am very graceful that I had the opportunity to work a number of weeks in the luminescence laboratory to learn the techniques for sample preparation and that Juan Ramon Vidal Romani is willing to pay the costs for OSL-dating my samples. Overall, the interest, willingness to help and social intercourse with all those people added an extra dimension to my work.

Chapter 1 Introduction

Research on catchment scale behaviour of fluvial systems has been a key topic in geomorphology during the last two decades. The increasing development of stronger computers and ever-increasing knowledge of fluvial systems enables fluvial geomorphologists to investigate rivers in more detail and on longer timescales by means of computer simulation models. The focus shifted from a descriptive approach based on solely sedimentology to a dynamic approach whereby tectonics, climate change and the internal system dynamics of a river are fully integrated. In Northern and Western Europe, focus is directed at the NW European basins where important alluvial river systems are found. Tebbens et al. (2000) demonstrated that in such a setting a river system experiencing isosynchronous climate and base level fluctuations will respond differently to them in different tectonic domains. Climate change governs river valley development in the system's middle and upper reaches whereas progressive aggradation in the subsiding lower reaches causes the build-up of a backfilling sedimentary wedge that forces the terrace intersection further upstream.
Using the same modelling approach, Veldkamp & Van Dijke (2000) showed for the Meuse that in the uplifting hinterland terraces register only glacial extremes and have a limited change of preservation. On the other hand, close to the tectonic hinge line (place where net uplift transfers to net subsidence) sensitivity to climate fluctuations generates the most complete and well-preserved terrace record.
One of the more recent works comes from Gargani et al. (2006) who used a modelling approach to deduct how, in the absence of detailed information on tectonic activity in the area, the initial river profile of the French Somme river could have looked like a million years ago. Using the outcome of their simulations, they were able to predict the most likable tectonic conditions operating in the region.
More numerical modelling based investigation encompasses work from Van den Berg (1996), Veldkamp & Van Dijke (1998), Veldkamp & Tebbens (2001) and Veldkamp et al. (2002).
Other regions in Europe are not so well investigated and research is still focused on the descriptive side of landscape development. It is therefore interesting to apply this modelling approach to another region with another geological setting. The study presented in this thesis focuses on the NW Iberian Miño-Sil system ("Minho" in Portuguese). The system is situated not in an alluvial basin setting, but in a mountainous bedrock environment where other tectonic and climatic operators drive the development of the fluvial system. The region is also challenging because the general lack of sediments makes a coherent reconstruction of the geological history virtually impossible. Hence, there are more conflicting ideas on the age and processes responsible for shaping the Late Cenozoic landscape than there is consensus. Especially the absence or presence of Quaternary tectonic uplift remains speculative. The main aim of the modelling exercise in this thesis is therefore geared towards testing a number of current hypotheses on the longitudinal profile development of the Miño-Sil system. This way some likely and improbable scenarios are presented and the factors controlling river gradient more constrained.

1.1 Research objectives

By using fieldwork and computer modelling techniques, this thesis aims at:

1. Determining uplift rates for the different blocks in the study area.
2. Determining if there is differential uplift on both sides of the lower Miño.
3. Elucidating how the Miño-Sil river system responded to late Cenozoic external forcing (changes in tectonics, climate and base level) and internal forcing (internal system dynamics).

4. Creating a better understanding of the importance of different tectonic regimes operating in NW Iberia.
5. Giving a synthesis of the available literature on the subject. The majority of literature is found in local Galician or Portuguese libraries and unknown to outsiders. A synthesis will therefore help facilitating further research.

1.2 Research questions

1. What happened in NW Iberia in terms of geological, climate and base level changes? These questions need to be addressed quantitatively.
2. What are the uplift rates for the different areas (tectonic blocks and basins) in the study area?
3. How did the Miño-Sil system adapt its course throughout the Late Cenozoic? What were the phases of aggradation and incision and where can they be located in the longitudinal profile? In order to find these answers, other matters need to be addressed first:
    - What were the effects of changes in regional (crustal extension and compression, isostacy) and local tectonics (tectonic block uplift and subsidence and lateral movements due to strike-slip fault regimes)?
    - How did climate change force fluvial behaviour?
    - How did base level changes force fluvial behaviour?
    - Where at present are alluvial terraces located and how much terraces are there?
4. Once the changes in river profile development have been reconstructed, the results can be used to better interpret the Cenozoic tectonic history of the study area and provide answers to the question what the tectonic regimes operating in NW Iberia during the late Cenozoic were like.

1.3 Outline of this thesis

This thesis is divided into three parts. In part I the theory concerning river behaviour and formation of river terraces is outlined. Additionally, the geological, geomorphologic and geographical background of the study area is presented.

Part II focuses on the fieldwork carried out in the lower Miño area. The fluvial terraces in this region have been a focus of investigation since as early as the 1940's (Vidal-Box, 1941; Lautensach, 1945; Teixeira, 1952; Butzer, 1967; Nonn, 1967; Alves, 2004) but up until now there is still no agreement on the exact amount of river terraces present. As knowledge on the amount and extent of terrace levels is paramount to the modelling exercise, fieldwork was conducted to establish the number of alluvial terraces present. In addition, information on the sediments that were selected for Optically Stimulated Luminescence (OSL) dating is given.

Part III deals with the modelling exercise. The numerical model, Fluver 2, is presented as well as the parameters and input of the model. The results of the modelling exercise are presented and discussed incorporating all important elements previously discussed in parts I and II. Part III also includes the final conclusion section.

The appendices contain all information that was collected in order to run the numerical model. This data comprises "raw" field data on fluvial terraces, information on the sediments collected for OSL-dating, information necessary to reconstruct fluvial terrace profiles and more. The final appendix contains a set of photographs illustrating the fieldwork and the natural setting of the Miño-Sil system in general.

Part I

Theoretical background

Chapter 2 Study area

2.1 Geology

2.1.1 Palaeozoic

The Iberian Peninsula consists of nine large tectonic units (Cotilla-Rodriquez & Cordoba-Barba, 2003). One of these units comprises NW Iberia and is in Spanish literature referred to as the “Macizo Hesperico”(Martin-Serrano, 1994; Cotilla-Rodriquez & Cordoba-Barba, 2003). See Figure 1. The Macizo Hesperico is a remnant of the collision between the North American and Eurasian plates in the Palaeozoic and Mesozoic, thereby forming the Variscan (Hercynian) fold belts.
In Iberia, the Hercynian orogenesis started during the Devonian and ended in the Carboniferous (Pinheiro et al., 1996 and references therein). The Late Hercynian deformation phase caused metamorphism of the Precambrian and Early Palaeozoic rocks into metamorphic crystalline rocks such as gneiss and metamorphic sedimentary rocks (slates, schists and sandstones), forming anticlinical fold belts roughly running NW-SE in the eastern part of NW Iberia (Martin-Serrano, 1994b). In central and western Galicia N-S running intrusions of plutonic rock associated with the Hercynian orogenesis can be found. The remaining part of NW Iberia consists of mainly granitic unaltered crystalline rock. The deformation also created numerous faults, mainly in a N-S, NNE-SSW, NE-SW, SE-NW and ENE-WSW direction (Yepes-Temiño, 2002 and references therein).

2.1.2 Mesozoic

During the Mesozoic, the Atlantic Ocean re-opened and the two plates drifted apart. The rifting and consequent crustal extension caused the generation of N-S trending faults in the western part of NW Iberia (Santanach-Prat, 1994). Because of this rifting, the west Iberian continental shelf is extremely narrow, varying between 65 km and 30 km at Cabo de Finisterra (Pinheiro et al., 1996).
During the Alpine Orogeny, the Iberian and Eurasian plates collided, forming the Pyrenees in northeastern Spain and the Cordillera Cantabrica in northern and northwestern Spain. The collision was associated with generation of NNE-SSW running faults (Santanach-Prat, 1994). Simultaneously, the Gulf of Biscay opened up causing a second rift off the Iberian continental shelf (Perez-Alberti, 2004) and subduction of the ocean crust under the Iberian plate resulted in uplift of the northern Galician Cabo Ortegal area and the emergence of the contemporary coastal strip in between the Cordillera Cantabrica and the Cantabrian Sea (Vidal-Romani, 1996).

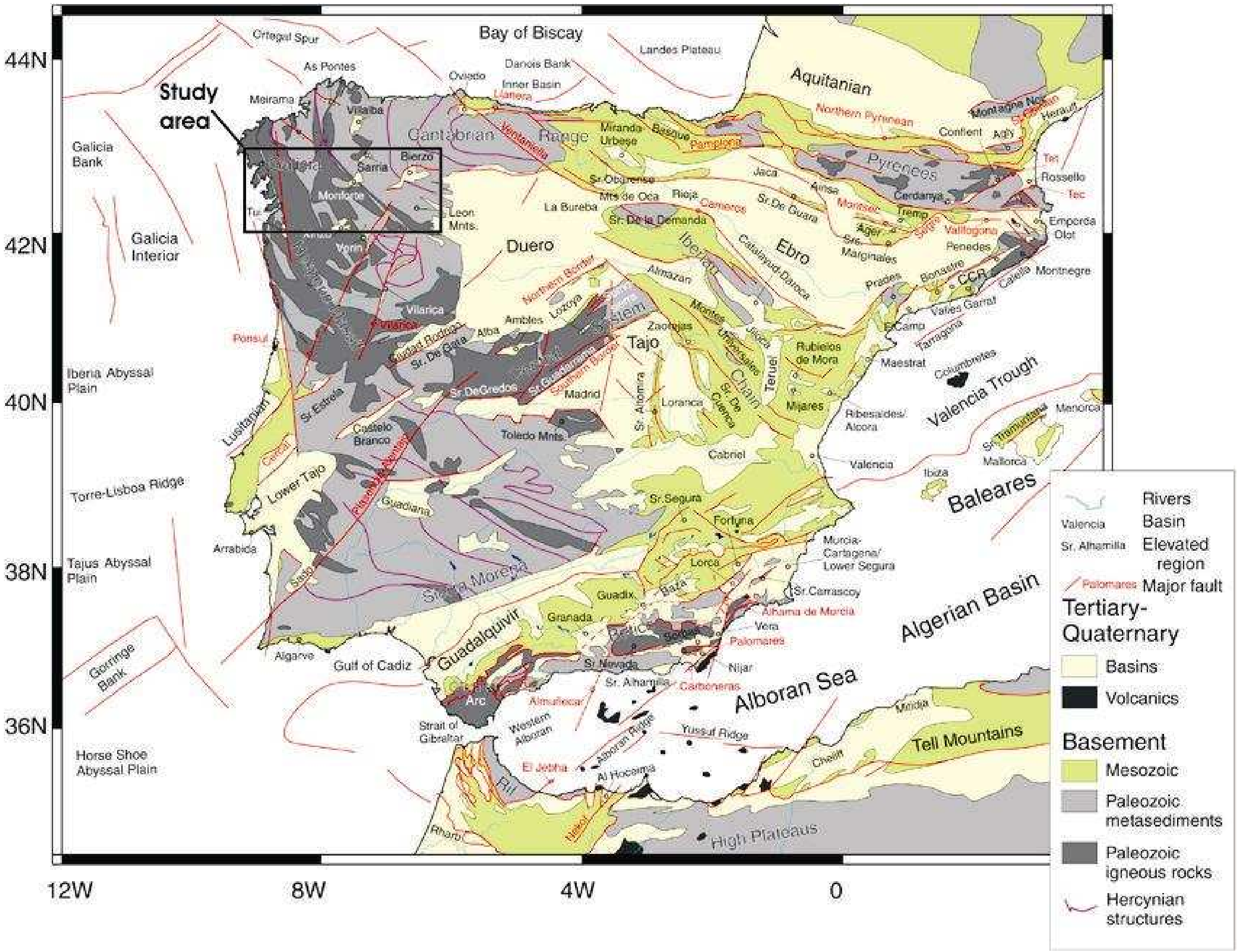

Figure 1. Simplified geological map of the Iberian Peninsula. Box in NW corner indicates study area. After Andeweg (2002).

2.1.3 Cenozoic

2.1.3.1 Tertiary

Alpine mountain building continued during the Miocene, causing a renewed uplift of the continent and consequently, the old Variscan fold belts. This promoted reactivation of many Hercynian normal faults (Tebbens & Veldkamp, 2001) and in combination with the ongoing uplift favoured the generation of horst-graben structures. Most Spanish workers agree with this idea (e.g. Hernandez-Pacheco, 1949 and Martin-Serrano, 1994b). According to them the mountains and basins in NW Iberia are consequences of subsiding blocks along fault lines causing a mosaic of hills and basins. This process is more intense close to the Galaico-Leonese mountains and levels out towards the coast. The most conspicuous horst-graben structures visible are the western Galician rias, many of whom have small islands at their outlets as a result from the nearby N-S running Hercynian fault lines. In Portugal, these rias do not exist. Possible reasons are discussed in Chapter 2.3.
Apart from the normal faults, the strike-slip faults in NNE-SSW to ENE-WSW played an important role as well. They seemed to be acting as normal faults during the pre-Alpine period, but behaved as reversed or thrust faults during the Alpine compression (Pinheiro et al., 1996 and references therein).
Although the idea is generally accepted that the Tertiary tectonic basins are a result of differential tectonic block movements, there is still much controversy on this matter. Some authors, for instance Santanach-Prat (1994), propose that the tectonic basins are related to compressional forces during the Pyrenean orogenesis. Others such as Perez-Alberti (1982) state that tectonic movements during the Tertiary caused a lessening of tension in the earth’s crust, resulting in the formation of numerous tectonic basins. These in turn are filled with Tertiary and Quaternary sediments.

2.1.3.2 Quaternary

The most important geological process during the Quaternary is the deposition of alluvial sediments and the formation of alluvial river terraces. The general thought is that the oldest alluvial terraces were already formed during the Pliocene (Herail, 1984; Pereira, 1991; Alves et al., 2000). The general outline of the fluvial net was already lain during the Tertiary and rivers did not change their course much afterwards (Martin-Serrano, 1994b). Fluvial incision continued throughout the Quaternary with a total estimated rate of 60-80 m (Vidal-Romani, 1989).

Close to the mountain areas in eastern Galician and Leon another kind of terrace is found. At the foothills of these mountains, gentle sloping platforms are found that consist of sediment originating from the mountains, very much like the wash pediment of the tropical shield areas. Fluvial action cut out terrace benches in these pediments, which are the *glacis* terraces. These terraces can contain a thin layer of alluvium as well. Sometimes the glacis and fluvial terraces are found together in one area, for instance in the Leonese Bierzo basin (Perez-Estaun et al., 1978).

In the mountain areas of Leon another typical deposit known as the *raña* formed. It very much resembles a sequence of alluvial terraces as it is found as bench-like sedimentary structures in the landscape, but it developed too high up on the mountain slopes to be of fluvial origin. There is much debate on its exact genesis, but it is generally agreed upon that the raña was formed during the Pliocene-Quaternary transition (Martin-Serrano, 2005 and authors therein).

During the Holocene, human influence was profound. As early as 5000 years ago, humans started to exert profound influence on the Galician landscape resulting in deforestation and subsequently, erosion. Important deforestation phases were the Late Neolithic, the Metal

Ages, the Roman period and the Middle Ages (Martínez-Cortizas et al., 2005; Mighall et al., 2006).

2.2 Geomorphology

The NW Iberian landscape is governed by fluvial processes. Fluvial incision started during the Tertiary as the Alpine uplift was so strong that the fluvial net could not keep up and antecedence was replaced by fluvial incision in weathering mantle and bedrock, causing deeply entrenched river valleys (Tebbens & Veldkamp, 2001). Additionally, the presence of a dense system of joint fractures in conjunction with high year-round precipitation and differential tectonic movements favoured the development of a complicated drainage system that took shape as early as the Tertiary. A major part of the Sil for instance runs through canyons and gorges of several hundreds of meters depth that are the result of the aforementioned processes. Up to twenty for the greater part, erosive terraces are reported to be chiselled into the hard rock of the Miño and Sil gorges and river valleys (Yepes-Temiño, 2002).

2.2.1 Age constraints of the landscape

The age of the deformations responsible for the current landscape is poorly understood. This is in the first place due to a lack of chronostratigraphical references. Fossils are hardly preserved in the acid soils and sediments of NW Iberia (Alonso & Pages, 2007), and sediments, albeit present, have hardly been dated due to the lack of dating facilities. Additionally the regional dispersion of the sediments contributes to an incomplete understanding of the general stratigraphy of NW Iberia. The attempts that have been made are diverse and contradictory (Martin-Serrano, 1994b). The sedimentological records of NW Iberia only have their terragenic character and their deposition in Tertiary basins in common. Their sedimentological, mineralogical and stratigraphical characteristics are almost incomparable. This makes it difficult to link the sediments of individual basins together in terms of regional genesis. The question is indeed if the basins can be linked together or not. If so, the problem arises that only an approximate age of Upper Oligocene-Neogene can be attributed. If not, the diversity in facies could be used as a criterion for stratigraphical superposition in a geological and geomorphologic context. This will however yield a discontinuous stratigraphy through time and space and only an approximate age of Palaeogene.

In principle, parallels in facies and sequences can be established for the Galician basins, the Bierzo basin and the western border of the Douro basin, but this information is of little use to date the many erosion surfaces of Galicia (Martin-Serrano, 1994a).

All these issues attributed to emerging contradictory hypotheses on the different morphotectonical phases of the landscape. There are two trains of thought:

1. Apart from older events such as the Alpine orogenesis, the re-organisation of the actual relief is quite recent. Tectonic activity prolonged from the Neogene into the Pliocene-Quaternary.
2. Tectonic processes are much older and did not play a role in the Quaternary. This is in line with evidence found on the continental shelf of Galicia, indicating that deformation took place during the Pyrenean orogenesis during the Palaeocene-Eocene (Martin-Serrano, 1994b).

2.3 Quaternary tectonics

2.3.1 Galicia and Leon

The most important tectonic phases took place during the Alpine mountain building phase. The formation of tectonic basins, block movements and fault rejuvenation in NW Iberia has traditionally been an important research area for French, Spanish and Portuguese researchers. Martin-Serrano (1989, 1994a) thoroughly investigated the Galician erosion surfaces and morphostructural blocks; Santanach-Prat (1994) investigated the development of the NW Iberian Tertiary basins and related fault development; Araujo (1990) studied the Neogene development of the basin of Ourense; Blanco-Chao et al. (2003) indicate that the Galician coast has been stable since at least the Eemian; and Perez-Alberti (2004) investigated the Tertiary basin of Maceda, just east of the Ourense basin and found indications of tectonic activity during the Tertiary and possibly the onset of the Quaternary, but not afterwards. All these authors agree on the importance of tectonic processes during the Tertiary, but fail to come up with evidence for Quaternary differential tectonic processes operating in Galicia or Leon. Martin-Serrano (2005, p. 78) even says that “el encajamiento que experimentan los rios no es la repuesta inmediata a un generalizado y reciente evento tectonico que afecta a toda la Meseta sino la secuela del rejuvenecimiento alpino experimentado algunos millones de años antes.” Literally translated this means: the incision that the rivers underwent is not the immediate response to a generalised and recent tectonic event that affected the entire Meseta [*Spanish Interior*] but the effect of the renewed Alpine uplift experienced some millions of years before.
Cotilla-Rodriguez & Cordoba-Barba (2003) extensively studied possible neotectonic movements for Galicia applying an integrated approach of geomorphologic and geophysical (seismic) techniques. They too found that the Galician interior lacks signs of neotectonic movement but in contrast to the aforementioned authors, they found moderate Quaternary tectonic movements in the northern and western coastal region of Galicia. They also detected strong Quaternary tectonic movement on the Galician/Portuguese border of the Miño region. However, they did not indicate until when exactly in the Quaternary the neotectonic processes were active.

It may be that some small regional tectonic movements occurred, as testified by the high seismic activity in the region (Cotilla-Rodriguez & Cordoba-Barba, 2003; Cloetingh et al., 2005), but tangible evidence for possible uplift has not been found. On the one hand, the lack of datable sediments makes dating of possible faults difficult. On the other hand, the existence of faults in itself is in many cases hypothetical, as they are difficult to observe (Cabral, 1995). Altogether this makes interpretation of block movement difficult (Yepes-Temiño, 2002).

2.3.2 Portugal

Cabral (1995) demonstrates that from the Upper Pliocene and during the Quaternary Portugal has generally been subjected to uplift. Only the lower Tagus river valley has been subsiding. In general vertical movement occurs either on a regional scale because of crustal deformation or crustal flexure; or vertical movement is triggered by concentrated crustal deformation. The latter usually takes place along faults or active flexures. Uplift shows a strong correlation with altitude: the higher mountainous regions in north and central Portugal experienced the strongest vertical uplift and the lower regions along the coast and in the south the least. Raised marine abrasion platforms and areas with marine sediments along the coast as well as deeply entrenched river valleys with flat valley floors and fluvial terraces in the interior support this theory (Cabral, 1995).
The Minho region however, is an exceptional case as the estimated vertical neotectonic movements do not agree at all with the general altitude of the region. This is due to the more complex tectonic history of the area (Cabral, 1995). A typical ENE-WSW (with small

inclinations to NE-SW and E-W) and NW-SE fault pattern dominates the Minho region. These faults do not follow the geological structures present, indicating that they are indeed faults. The major rivers of the area and especially the Cavado and Lima rivers, follow these faults (Cabral, 1995).

Cabral is not the only one who recently found evidence for Quaternary uplift in Portugal. For a long time scientists assumed the Portuguese coast to be tectonically stable (Araujo, 2000). The last twenty years however, clear indications have been found that a large part of the Portuguese coast is indeed tectonically uplifting. For instance Granja (1999) and Granja et al. (1999) describe Quaternary age faults at Figueira da Foz and contorted bedding in a slumped bed in between the Neiva and Cadava rivers and more Pleistocene and Holocene faults at a beach south of Espinho. Furthermore, Araujo (2000, 2004) found granites overlying Eemian deposits because of a thrust fault and uplifted shore platforms in the coastal zone of NW Portugal.
It follows that there is a clear discrepancy between the neotectonic regimes of Galicia/Leon and Portugal. Possibly the unequal amount of research carried out in both countries forms part of the explanation. On the other hand, as we have seen, the lower Miño follows a direction that is the same as the general direction of the rias and the major rivers in northern Portugal. The Miño is also the only major river in coastal Galicia that is not part of a ria and rias do not exist at all in Portugal. Nonn (1967) and Cabral (1995) propose that the Miño possibly flows through a major fault. This seems to indicate that the lower Miño is the exact boundary of two distinct tectonic regions: an uplifting Portugal and a tectonically stable Galicia. This is not a new theory. Already in the thirties workers proposed that the formation of the Galician rias was to be attributed to a Pliocene lowering of the Galician and Cantabrian coasts relative to the northern Portuguese coast (Pereira, 1989). They were wrong in the sense that Galicia is not subsiding, but even so, we have to keep in mind that the lower Miño is flowing on the contact of two regions with possibly different uplifting regimes. This may have consequences for the location and the amount of river terraces found on both sides of the lower Miño river. This matter will be explored more fully in Part II of this thesis.

2.4 Climate

Throughout the Mesozoic a tropical humid climate prevailed, which in combination with a lack of significant tectonic disturbance until the onset of the Alpine orogenesis caused the formation of a deeply weathered bedrock mantle. Then, during the Eocene in general a tropical warm and humid climate prevailed (Perez-Alberti, 2004), causing deep and strong weathering of the crystalline rocks. This in combination with the long period of tectonic quiescence levelled the landscape to undulating peneplains.
After the Miocene climate became increasingly drier resulting in a dry, subtropical climate, comparable to the Mediterranean climate today (Perez-Alberti, 2004).
During the Quaternary glacials, NW Iberia experienced periglacial conditions and glacial conditions in the mountain areas (Valcarcel-Diaz, 1995; Valcarcel-Diaz and Perez- Alberti, 1996) and temperate humid conditions during the interglacials. Because of the presence of severe cold conditions and permafrost overland flow and slope processes became key factors in shaping the landscape. Consequently, the deeply weathered Tertiary sediments were all removed and deposited in either the sedimentary basins or the sea. The Galician rias acted hereby as efficient sediment traps (Dias et al., 2002ab; Garcia-Garcia et al., 2005 ; Mendez & Vilas, 2005). These processes left the NW Iberian landscape behind as one of bare rock.
During the last glacial vegetation shifted from steppe to open woodland following millennia-scale climatic oscillations. The rapid response of vegetation to these changes suggests the existence of forest refugia in the region (Roucoux et al., 2005).

At the moment, NW Iberia experiences a temperate maritime climate near the coast with high annual rainfall. Summers are relatively cool and winters soft with temperatures hardly ever below zero. Mean annual precipitation values for the coastal provinces of A Coruña and Pontevedra are 1342 mm and 1402 mm respectively. The coastal mountains receive 1800 to 2000 mm. Mean summer temperatures are 19.7 degrees and mean winter temperatures ~9.5 degrees (Martinez-Cortizas et al.). Inland the climate becomes markedly more Mediterranean with less rainfall. Ourense province for instance registers mean precipitation values of 994 mm a year with local minima of 500-600 mm in the Miño-Sil valley (Martinez-Cortizas et al.). Mean values for the entire Miño-Sil catchment are estimated at 1350 mm a year (Rio-Barja & Rodriguez-Lestegas, 1992). Mean summer temperatures for Ourense province are 17.9 degrees with lower winter temperatures of 6.9 degrees (Martinez-Cortizas et al.). Frost and snow are common in the eastern and southern mountain ranges.

2.5 Overview of the study area

The Sil starts in the southern Cordillera Cantabrica in the province of Leon at an altitude of 2000 m just east of the village of Villablino. See Figure 2. The area has typical anticlinical fold belts known as the Antiforme de Narcea and consist for the major part out of Palaeozoic slates, sandstones and quartzites that were deformed during a number of compressive tectonic phases in the Hercynian and Alpine periods. The Sil runs through a series of deeply incised canyons resulting from omnipresent N-S and NE-SW running fault lines. These canyons are alternating with small intramontane Tertiary basins where river terraces are abundant, notably around the village of Paramo del Sil and in the small basin of Noceda del Bierzo.

Directly southwest of the city of Ponferrada the Sil enters the large Tertiary intramontane basin of the Bierzo. The basin is filled with Cenozoic sediments, mostly Pliocene conglomerates, gravels, sands and clays. Being a local depression a number of rivers congregate in the Bierzo. These are the rivers Cua, Burbia, Boeza and naturally the Sil. Associated with these rivers a large number of very broad river terraces and glacis terraces can be found.

Shortly after passing the city of Ponferrada the Sil enters the Galician/Leonese Valdeorras area where deep canyons again alternate with a number of Tertiary sedimentary graben basins. These are the basins of Carucedo, O Barco, A Rua de Valdeorras and Quiroga. The region is famous for its ore deposits of which Las Medulas is the most famous area. It was once the Roman empire’s most important area for mining of ore deposits and especially gold. The excavated reddish sandstone peaks are still a remarkable feat in the predominantly green landscape.

After Quiroga the Sil enters the Garganta do Sil, the deepest gorge in the area, before meeting the river Miño at the village of Os Peares. It passes by the basin of Monforte de Lemos without entering it due to antecedence (Martin-Serrano, 1994b). From here on the geology changes from Palaeozoic metamorphic sedimentary rocks to Palaeozoic and Precambrian crystalline and plutonic rocks, in the form of mainly granites and granodiorites. The Miño’s course is still dictated by structural control (faults), but the Tertiary sedimentary basins and abundance of fluvial terraces are no longer found until the Miño passes by the city of Ourense. Here again a flight of alluvial terraces marks the landscape until the village of Ribadavia. After Ribadavia the Miño becomes the natural border between Galicia and Portugal at the town of Melgaço and its course is being dictated by a huge fault line. After the town of Salvaterra and close to the Atlantic Ocean the Miño widens up considerably, supposedly due to a combination of high sea levels and a warm and humid climate during the Upper Pliocene (Pereira et al., 2000). It is in this area where the highest number of terraces is found and the fieldwork for this MSc thesis is conducted.

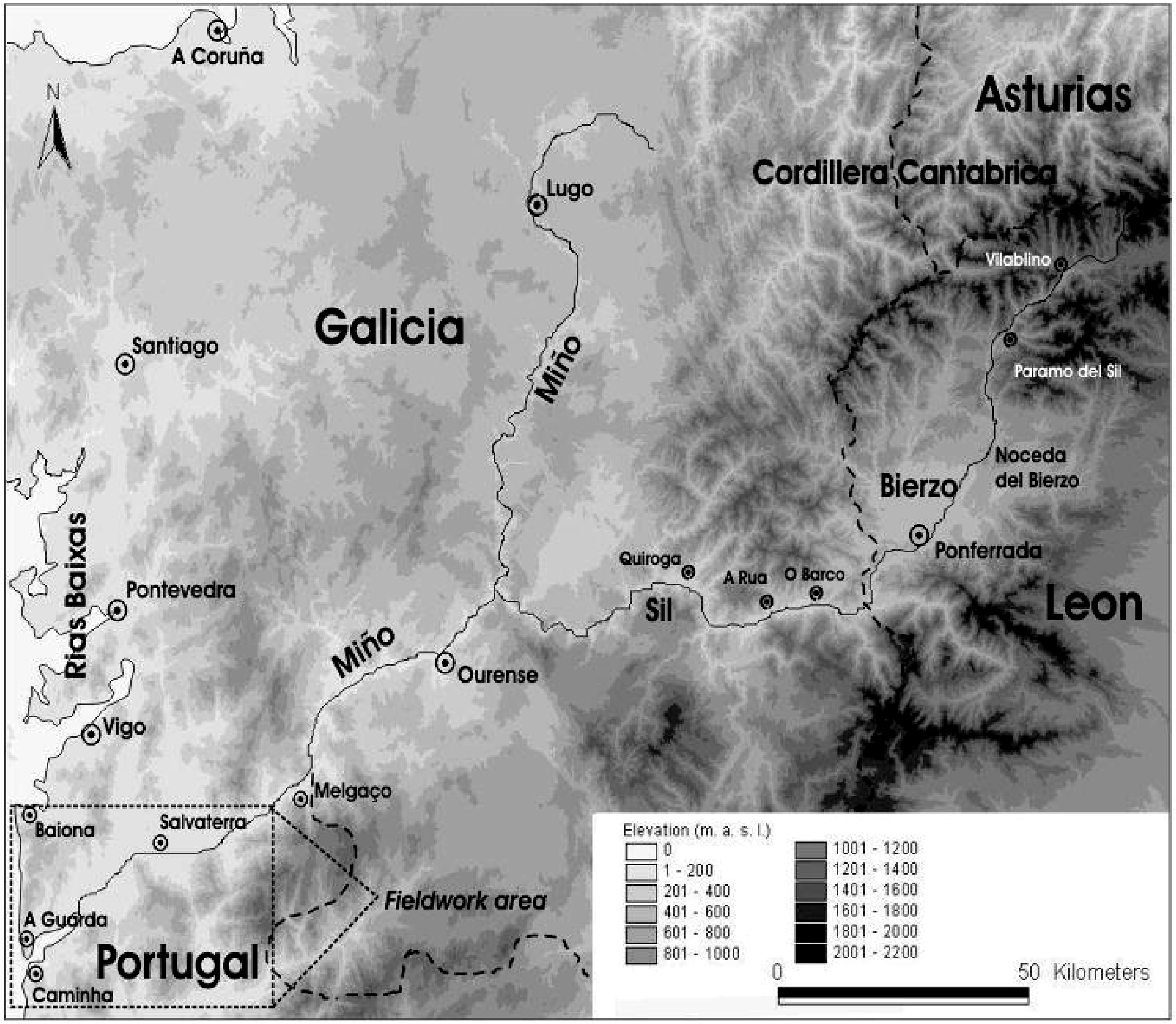

Figure 2. Overview of the study and field work area. Dashed lines indicate regional borders. Dots indicate cities and villages. For close-up of field work area, see Figures 3 and 4.

Chapter 3 Theory on fluvial systems

3.1 Morphology of rivers

3.1.1 River types

Rivers can be subdivided into four categories (after Nichols, 1999):

1. Straight channels. These are single channels without dividing bars and a low sinuosity (< 1.5)
2. Meandering rivers. Highly bended channels with a sinuosity > 1.5. The bends change shape due to changes in erosion and deposition on their banks. The inner bank usually shows signs of deposition and the outer bank shows signs of erosion.
3. Anastomosing rivers. These rivers contain several channels that join and separate along the river profile.
4. Braided rivers also have several channels but show signs of deposition in between their channels. These depositional environments are called bars.

In terms of palaeoenvironmental reconstructions, meandering and braided rivers are most important. These river types deposit recognisable sediments, usually in the form of alluvial terraces (Nichols, 1999).

3.1.2 Factors controlling river type

Factors controlling river type are gradient, vegetation and the proportions of bed load and suspended load. Anastomosing rivers usually form in relatively flat areas with instable banks, whereas braided and straight channel types form in areas with a slope > 0.1 degree. Meandering rivers tend to form in areas with less steep slopes (Nichols, 1999).

3.1.3 Factors controlling discharge

The river catchment is the area that supplies water to the river's main channel(s). The catchment area consists of various smaller rivers and streams that form a dendritic pattern congregating in fewer channels until finally one main channel remains. The streams and channels are fed by rainwater and/or groundwater and flow downstream.
Two factors control the supply of water to a river system: size of the catchment area and climate. A small catchment area has less soil surface to soak up precipitation and hence, will have a smaller buffer capacity for changes in water supply.
Climate is important as it controls the amount of water in the system per time unit. If rainfall is highly variable in a short time span, for instance during a tropical monsoon, the soil will not be able to buffer this amount of rainfall. Consequently, the streams in the catchment area will transport large amounts of water in a relatively short time span (Nichols, 1999).

3.2 River valley formation

The old Hercynian (Variscan) massifs experienced renewed uplift during the Alpine orogenesis. Before then they had been stable landscapes for a long time. This resulted in low horizontal surfaces (peneplains) where rivers were flowing in their own alluvium. The renewed Alpine uplift caused the rivers to cut into their own alluvium and after that into the underlying bedrock. This combination of strong uplift and cutting into the bedrock created deeply incised river valleys, a common feature in NW Iberia. This incision was initially asymmetric. If the rivers had enough stream power to keep up with the tectonic uplift, they were even able to cut their meandering forms into the bedrock. This capacity to keep their original course is called antecedence and the capacity to cut their original form into the bedrock is called epigenesis (Tebbens & Veldkamp, 2001).

3.3 River dynamics in relation to terrace formation

A river is a sensitive geomorphologic system. It constantly adapts itself to changes in tectonics, climate and base level to reach a state of dynamic equilibrium. Such a river is called a graded river (Bull, 1991). A fluvial system in equilibrium will typically have a concave profile (Bull, 1991). On the other hand, a change in one of these three conditions leads to changes in discharge and sediment supply which in turn govern the internal dynamics of a fluvial system. For instance, changes in discharge and/or sediment load may trigger changes in channel width, channel depth and stream velocity, causing a river to attain braided, anastomosing or meandering properties (Bull, 1991). In this way, a river seeks to establish a new equilibrium. In turn, all these factors determine if, where and when fluvial terrace formation occurs.
The three main drivers in terrace formation, namely tectonics, climate and base level, are discussed into more detail in the subsequent sections.

3.3.1 Tectonics

An area may experience local or regional uplift, for instance due to compressional tectonic forces or because of glacio-isostacy. This will lower the base level and consequently a river will start to incise in its own alluvium, or in a later stage, in the underlying bedrock. This incision will start at the rivers former mouth and will gradually extend upstream. This process of upstream erosion is called head ward erosion (Tebbens & Veldkamp, 2001).
On the other hand, local or regional subsidence due to for instance crustal extension causes a rise in base level and fluvial aggradation. This does not directly lead to terrace formation, even though it is part of the process.

3.3.2 Climate

Most fluvial terraces are formed during the Quaternary when there was a rapid change in climatic conditions. During glacial periods most water on Earth was locked up in ice masses, which altered the global water balance and caused a lowering of global sea level and thus base level. This in turn caused an increase in river gradient and rivers started to incise. During an interglacial sea level rises and the river gradient becomes less. This decreases overall stream power and the river is no longer capable of transporting sediment. In this case, the river starts aggradating.

During a glacial vegetation is absent and permafrost inhibits water infiltration into the soil. In a relatively wet period these factors cause surface run-off resulting in erosion and consequent sediment supply into the river. During an interglacial, this process is reversed as vegetation stabilises the slopes.

These processes contradict the theory of glacial incision and interglacial sedimentation. In practise, glacial incision and interglacial sedimentation occur in the lower reaches of a river system and glacial sedimentation and interglacial incision in the upper reaches (Tebbens & Veldkamp, 2001).
Another model is developed by Bridgland (2000), who proposes that terrace formation takes place in six steps. The main aggradation phases occur in the transitional phase from glacial to interglacial and visa versa.

Of course, this is a very simplistic approach. Bull (1991) describes his complex response theory whereby sudden short changes in one of the external parameters will cause the river to adapt its behaviour more than one time. This could cause local terrace formation.

3.3.3 Base level

Formation of fluvial terraces is usually linked to changes in sea level. A drop in sea level facilitates fluvial incision and a rise in sea level causes aggradation. This effect is more pronounced downstream a fluvial system where a sedimentary wedge may be built up through time (Merritts et al., 1994).

3.4 Morphology of river terraces

3.4.1 Genesis of river terraces

An alluvial terrace is formed when a river deposits sediments in the river valley. This happens when the transported sediment load exceeds stream power. During such periods of aggradation, a thick layer of fluvial sediment is deposited on the valley floor. When base level drops due to either tectonic uplift or an absolute lowering of sea level, a river may start to incise in its own alluvium. This also depends on the erosion potential of the stream itself. When the river carries little sediment load, the erosion potential will be greater. And if the incision is deep enough, a terrace scarp is formed. This type of river terrace is formed when a large supply of sediment is available compared to water availability and the incision rate is not too high (Veldkamp & Van den Berg, 1993). As conditions change and a river starts to aggradate again, a new terrace scarp will form. In the end, a set of flat, staircase-like benches will form, with the oldest terrace taking up the highest position in the valley and the youngest terrace the lowest position just above the river floodplain. The elder terraces are usually severely eroded or cut through by streams that developed afterwards.

Another kind of terrace is the strath terrace. This type forms when the incision rate is very high or sediment supply very low, for instance in a rapidly uplifting tectonic setting. In this case, the river needs to keep up with the uplift and does not have time or material to aggradate and only a small layer of sediment will form on the valley floor. During a period of incision the river will incise through this layer and straight into the underlying bedrock (Summerfield, 1991).

The two types mentioned above are ideal situations. In the case of quick alternations of aggradation and incision intermediate terrace types may form. These quick alternations are the result of the river adjusting its internal parameters (Bull, 1991).

3.4.2 Terrace location in relation to floodplain

Generally the relation between vertical spacing of river terraces and floodplain can be subdivided into three different situations (after Summerfield, 1991):

1. Terraces can be situated in a parallel arrangement with respect to each other and the floodplain. This generally indicates a synchronous uplift throughout the river area.
2. Terraces can diverge downstream indicating little or no uplift. Terrace formation is in this case probably controlled by drops in sea level.
3. Terraces can converge downstream indicating repeated local tilting of tectonic blocks.

Furthermore, terraces may be paired or unpaired. Unpaired terraces may form when lateral shifting of a river erodes certain terrace levels on one side of the valley. Paired terraces form when incision is rapid and a river does not have the opportunity to migrate laterally sufficiently (Summerfield, 1991).

3.5 Sedimentology of river terraces

The sedimentology of alluvial terraces is highly diverse as it varies from reach to reach within a river system and laterally and even locally. For instance, in the strongly uplifting hinterland of a catchment, the river gradient is steeper and thus stream power is greater. Consequently coarser sediment is transported and will be deposited as the carrying capacity drops below a certain threshold value. On the other hand, in the lower reaches of a river channel gradient is less and finer sediment will be deposited.
Lateral variations can be found between the river channel and floodplain as gravel is usually deposited in river channels and finer material on the floodplain (Nichols, 1999).
Then there are local variations that depend on for instance river morphology. Braided rivers typically have gravelly cross-bedded units representing bar deposits or gravel lags on the bottom of channels. Meandering rivers in the lower reaches tend to flow in wide valleys where overbank deposits in the form of fine silts are easily preserved (Nichols, 1999).

River terrace sedimentology is a world in itself and it goes too far to treat all the different aspects. From a practical point of view, it is most convenient to use existing data on river terrace stratigraphy for the study area. This will be treated more fully in the “Methods” Chapter of Part II.

Part II

A case study: fieldwork in the Lower Miño

Chapter 4 Methodology

4.1 Literature review

In Wageningen information was collected on research done with the model Fluver 2, past climatic data for the study area and past sea levels. Finding information on the physiography of the study area proved to be very difficult as the study area is not well investigated by the international scientific community. Information in Spanish was available, but not in Wageningen. Much of the needed information on the study area was therefore obtained in Santiago.
Information on the Portuguese side of the Miño (or Minho in Portuguese) was to some extent available in the library of Santiago. The remaining articles were obtained from the university library of A Coruña and from the university library in Porto (Portugal). I never read Portuguese before but I rapidly got used to it.

4.2 Digital Elevation Model

In Wageningen a Digital Elevation Model (DEM) with a grid cell resolution of 3 Arc Seconds (92,73 m) was created for the Miño-Sil catchment. The Spanish part of this DEM was downloaded from the United States Geological Survey (USGS) website. The Portuguese part of the river Minho was not available on the USGS site but was obtained through contacts with a Portuguese scientist. The DEM was used to gain a general overview of the study area.

4.3 Fieldwork preparations

4.3.1 Focus

Fieldwork is carried out with the following aims:

1. To determine the maximum amount of terraces in the study area.
2. To use these terraces to reconstruct Quaternary uplift rates. These rates will serve as input for the Fluver 2 modelling exercise.
3. To look for signs of tectonic activity. The scientific community is contradictive on the existence or non-existence of Quaternary tectonics in Galicia. Fieldwork may attribute to new insights.
4. To find enclosures suitable for sampling. These samples are used to date terrace levels with OSL-dating techniques.

4.3.2 Selecting an area for fieldwork

The Miño and Sil rivers are for the greater part running through faults in a mountaineous region. Terraces are found only in the intramontane basins and in the lower reach of the Miño. The Leonese Bierzo would have been a suitable place for terrace inventory, but aerial photographs were not available, making this area a non-possibility. Within Galicia/Portugal the lower 52 km of the Miño were selected for fieldwork for the following reasons:

1. Existing literature indicates that this area contains most terrace levels. This in itself is interesting enough, but the aim of the fieldwork is to find terrace levels in order to determine uplift rates for the river system. The more terrace levels we find, more detailed we can reconstruct the tectonic uplift of the area.
2. Cotilla-Rodriguez & Cordoba-Barba (2003) indicate that within the Miño-Sil river system in Galicia only the lower reach of the Miño experiences tectonic activity. This gives reconstructing uplift rates in this area some sense.

3. Existing literature is contradictive on the amount of terraces found in this region. Reconstructions vary from 3 to 7 terraces. A new terrace inventory can therefore shed more light on this dilemma.
4. The lower Miño is bordered by Galicia on one side and by Portugal on the other. Since Lautensach (1945) there has been no one who has investigated both sides of the Miño. For this reason knowledge on the terraces is fragmented and incomplete. A new fieldwork campaign incorporating both sides will help generating a holistic overview.

4.3.3 Aerial photographs

Aerial photographs with scale 1:20.000 for the Spanish side of the Miño were procured in Santiago de Compostela. Photographs with a scale of 1:25.000 for the Portuguese side of the Miño were collected in Portugal during a visit to the University of Porto.

4.3.4 Maps

Geological maps (1:50.000) and topographic maps (1:25.000) for the entire Miño-Sil river area were obtained in a number of university libraries in Santiago. The ones not available I downloaded from the website of the Spanish geological survey.
Geological maps (1:50.000) and topographic maps (1:25.000) for the Portuguese side of the Minho were obtained in Porto.
A 1:250.000 scale topographic map of Galicia was bought in a bookshop in Galicia and a similar topographic map for the Sil catchment in Leon was bought in Ponferrada (Leon).

4.3.5 Identitying areas suitable for field research

Because of the extent of the area and the limitied time available, a selection was made of areas to visit. By interpreting over 70 aerial photographs, geological maps and existing literature a number of transects was set out in such a way that it would yield a representative overview of the entire area. In an ideal situation an even number of transects would be set out on both sides of the river in a parallel alignment with a fixed space in between transects. Unfortunately the Miño terraces are very eroded leaving areas without little to no sediments and therefore this method cannot be applied. Transects had to be set out where the geological map dictated there were sediments left and then the aerial photographs were used to delimit possible terrace transitions. This method proved to be a successful way of finding terrace remnants in the upper and middle reach of the study area. For the lower reach of the Miño this method could not be applied. The last 13 km are severely eroded leaving only bedrock and small patches of terrace material. On the aerial photographs flat surfaces and scarps were still visible, but fluvial sediments could not be found and thus the absolute proof that a flat surface is a fluvial terrace could not be given. After a number of unfruitful days I had to change tactics and I reverted to locating terrace remnants using the geological map and existing literature only. Teixeira's (1952) work proved to be very useful finding terrace remnants on the Portuguese side. For the Spanish side such useful literature was not available meaning that this side was not investigated as thoroughly.

4.3.6 Data inventory

To work as methodological as possible, I developed two different fieldwork sheets which I filled in for each location I inventoried. One sheet is for the description of all aspects relevant to terrace location and the other for the sedimentology and stratigraphy of the enclosures encountered. These sheets are found in Appendix 1.

The Spanish and Portuguese topographic maps use a UTM ED 1950 projection. Therefore the GPS was installed with UTM European Datum 1950, zone 29N.

4.4 Fieldwork

4.4.1 General

Because of the absence of funding, I could not rent a house in the study area. To overcome this problem I used my camper van to sleep in and to move around in the study area. The advantage was the mobility it gave me, the disadvantage that during prolonged periods of rain I could not work. My GPS and maps would get wet without any possibility of drying them, not to mention myself. Hygiene and loneliness as well posed a problem. For this reason I split up my fieldwork in periods with a maximum of ten days. All fieldwork took place between March and June 2007.

The fieldwork period started with an initial 8-day survey of the area to get a general impression. During this period, it became clear that the area had suffered much from the viniculture. Many of the slopes are terraced which makes identification of terrace scarps in some cases impossible. Especially the Galician side of the Miño suffered enormously from some landscape-level bodegas.
A second aspect is the ongoing road construction. Galicia has always been an outpost of Spain and the inaccessible and mountainous landscape has been a hindrance to a decent infrastructure. Large-scale EU-funded road construction projects have changed this with dramatic effects for the landscape. Roads tend to be build where the landscape is flat and of course, river terraces are the perfect location.
Gravel pits are another factor causing severe erosion in the area. As NW Iberia mainly consists of hard rock, gravel and sand used for the building industry is scarce. The Miño terraces consist mainly of gravel and sand and consequently a vast amount of excavations is going on.

4.4.2 Terrace inventory

4.4.2.1 Identifying terraces

Terraces were investigated by means of a predetermined transect. In most cases I started at the river floodplain and made my way upslope to the highest terrace on the transect. I tried to walk in a straight line perpendicular to the river and terrace scarps as often as possible but this was more than once made impossible by obstructions such as fences, ditches, impenetrable forests and fierce dogs. Because the terraces are very eroded and cut through by small streams, I tried to walk upslope in a straight line on the highest ridge in between two streams, the idea being that the highest area in between streams most likely represents the least eroded terrace surface.
Terraces were recognised on basis of their morphology rather than on their sedimentology. They were very conspicuous elements in the landscape with a high terrace scarp (many times as a massive 10 meter wall), a flat surface and the presence of rounded to sub-rounded gravel. In order to be catalogued as a fluvial terrace all three elements had to be present. At higher elevations sometimes flat surfaces with a terrace scarp were found, but without the presence of sediments. Although these surfaces are probably former terraces they were not catalogued as fluvial terrace, but as “bedrock”. As the landscape is made up of bedrock mountains and no other sedimentary features can be found, flat surfaces with rounded gravel were automatically river terraces. The only problem was to differentiate *between* terraces as the terrace scarps were sometimes eroded changing an otherwise stepped slope in a smoothly inclining slope. In this case, the transition from a flat surface to a slightly dipping slope was used as a criterion for a terrace transition.
Manmade features were also useful in identifying terraces and terrace transitions. In Galicia for example the railroad in between the villages of As Neves and Tui can generally be found around 30 m altitude, this always being the one and the same terrace. Old roads tend to run parallel to and adjacent to terrace scarps without crossing them, thus marking terrace

borders. The same goes for old trees and tree species, marking the transition of the wet (former) floodplain to the youngest terrace. Old buildings and especially graveyards and churches are always built on flat surfaces and never on the floodplain. Additionally, churches are normally built on the highest flat surface in the area, making identification of a possible highest terrace level rather straightforward. Stone walls were another very useful item as local people tend to use building materials that are close at hand. One could literally see a transition from walls made up of rounded fluvial cobbles on river terraces to walls with a mixture of cobbles and bedrock stones to walls with only bedrocks in areas without fluvial sediments. My colleagues in Santiago refer to this as “tapeologia” or “murology”, the art of wall recognition.

I did not use their sedimentology to differentiate between river terraces. This would cost an immense amount of time and there were not enough enclosures for this kind of work. Besides, the sedimentology is quite homogeneous. The terraces consist almost entirely out of a mixture of sandstone, quartz and quartzite cobbles with sizes of in between 5 and 25 cm. These cobbles are imbedded in a matrix of either sand or sandy loam, sometimes concreted and sometimes not. The overall colour of these conglomerates is whitish to yellow-whitish to yellow-reddish. Butzer’s work (1967) shows that there is only a slight variation in percentage sandstone, quartz or quartzite cobble in between terraces. Pereira (1991) demonstrates that the older terraces have a matrix with an higher kaolinite content, but this is not a useful characteristic either in a field situation.

The idea to record the sedimentology and stratigraphy for a number of enclosures was quickly abandoned. The gravel pits and road works exhibit a number of very large enclosures of high quality. It would take many weeks to describe them properly. The fieldwork form I developed to describe enclosures was therefore never used to this end. I did use it to record the data for the enclosures that were selected for OSL-dating. Drawings were not made as digital photographs are a far easier and better alternative.

4.4.2.2 Measuring terrace heights

The position where the terrace scarp started (terrace base) was measured by taking the coordinates with a GPS and the altitude was estimated by using a 1:25.000 topographic map with 10 m contour interval. The terrace height was determined by taking the coordinates right above the terrace scarp, or in the case of a slightly dipping slope, where the terrace surface flattened. Coordinates were plotted onto the 1:25.000 topographic map. In general, the start of the terrace scarp, the so-called terrace base, was found on the same altitude as the terrace surface of the former, lower situated, terrace. If a terrace surface was flat but still slightly inclining, the maximum height of this surface was measured also using GPS and topographical map to prevent measurement errors for the next terrace. The T1 terrace for instance has a terrace surface that rises away 6 m.
During my fieldwork in Galicia, I encountered many problems with the Silva GPS I took from Wageningen. It would take very long to find my position, sometimes up to one hour, and in a number of occasions, the coordinates proved to be incorrect, making my measurements worthless. In forest, the GPS worked hardly at all. This was very inconvenient as half of the terraces was covered by eucalyptus forest.
To solve this problem I borrowed a Garmin Emap GPS in Santiago for my fieldwork in Portugal. Apart from being capable of taking coordinates in whatever conditions within a few seconds, the GPS also had an altimeter using satellites for altitude measurements. I tested the GPS on a number of locations where the altitude was known. In the open field the GPS was able to measure height with an accuracy of 1 to 0 m. In open spaces in forest a precision of about 1 to 5 m could be maintained. This made the GPS a prime tool for measuring terrace heights. I checked all measured heights against the heights as given by the 1:25.000 topographic maps and decided on the spot what the more accurate height was.

The Portuguese maps are far better than the Spanish ones with interpolations in between the 10 m contour intervals. This made height comparison in Portugal easy and straightforward. All field data is found in Appendix 2.

4.4.3 Inventory of signs of tectonic activity

All enclosures were investigated on the presence of faults. No faults were discovered.

4.5 Data preparation and data analysis

4.5.1 Refining height measurements

All points with height measurements for the Galician side were plotted into a 1:5.000 digital topographical map with a 5-m contour interval. The map as well had a European Datum 1950 and a UTM projection. This made it possible to refine the height measurements up to an error margin of 5 m instead of the 10 m error margin using the 1:25.000 topographical maps. At the same time I checked if the locations where I made my measurements made any sense and if they represented a regional terrace level or local one.

4.5.2 DEM usage for plotting observations and base-line reconstruction

To be able to use my field observations with the DEM, I first had to convert the DEM from WGS84 datum to ED50 UTM projection and refine this datum to a local datum suitable for the Spanish/Portuguese border. I did so using the ArcView “Projection Utility”. I then plotted all my field observations into the DEM and using the river as the base line, drew perpendicular lines from the field points on the Miño base line. The rationale being that a perpendicular line represents the shortest distance from the field point (terrace level) to the river. This is necessary because all points need to be at the right position along the base-line. If not, strange jumps in the constructed terrace profile may occur. In doing so I had to assume that the Miño has not changed course throughout the studied period. The terrace transitions in the geological maps do not indicate any significant changes in channel direction and therefore I consider this a valid assumption.
This method in itself is not very exact, but because the river gradient is low (the youngest terrace surface depicts 4 meters altitude difference over 52 km length), the neighbouring field points representing the same terrace will consequently have the same height. Thus, it is unlikely that any major errors will occur using this method.
After all the field points had been connected to the base line I measured the distance from the field point at the beginning of the field work area to the next ones using the Arcview ruler. I made sure that the unit was set to kilometres.

4.5.3 Terrace profile reconstruction

Now that the terrace height and a place along the base line are known, a curve can be reconstructed placing the terrace height along the Y-axis and the place along the base line along the X-axis. This was done in Excel. To determine to which terrace level a measurement belongs field notes were used. During the fieldwork terrace order on a transect was written down. The transects close to the villages of Salvaterra, Caldelas, Sobrada, Barbeita, Troviscoso and Friestas contain either a complete set of terraces or a set with only one level missing. These transects provided the framework in which to place all terrace levels.
A second help was the terrace height itself. Because the river almost runs at sea level and has a very low gradient in the study area, absolute terrace heights can easily be compared and directly plotted into a curve. In doing so I had to assume that all terrace levels maintain the same gradient along the river. Older, erosive terrace levels in the Miño are found to

maintain the same gradient with respect to each other and the river indicating a regional homogeneous incision of the Miño during the Cenozoic (Yepes-Temiño, 2002). Cano-Pan et al. (1997, 1999a) mention that the terrace levels they found can be followed throughout the study area at the same height, which suggests that there has not been any uplift or subsidence of tectonic blocks. I myself did not note any jumps in terrace heights during fieldwork. Overall, Quaternary individual block tilting has not been reported for the lower Miño area so the assumption that all levels occur at more or less the same height and maintain the same gradient seems justified.
To link all individual measurements of one terrace level together, a trend line was used.

In total 174 out of 225 measurements were used for terrace profile reconstruction. 51 measurements were not used for the following reasons:
-17 measurements describe bedrock or colluvium where a terrace could have been present as indicated by aerial photographs, geological/topographical maps and literature.
-During the first days of fieldwork in Galicia 18 measurements turned out to be incorrect because of the GPS failing to display the correct coordinates. This was noticed only afterwards and these measurements were immediately erased from the list.
-At the coast 3 terraces were investigated which, according to the geological map and Teixeira (1952), are part of the Miño terraces. I think that these terraces are not Miño terraces as they fall outside the Miño catchment area.
-In Galicia manmade terraces obscured natural terrace transitions. To overcome this problem possible terrace transitions were marked and the best option chosen while reconstructing terrace profiles. This made 13 measurements redundant. These measurements can be found in brackets ( ) under the header “terrace #” in Appendix 2.

4.5.4 Terrace height calculation

A linear trend line was plotted through all points of the same terrace level (see Figure 5). The Figure and appendix 3 show there is a certain variation between data points within a terrace level. This variation is in most cases more than 5 m. In the T4 terrace for instance, height measurements vary between 36 and 44 meters. Even the data points for the youngest T0 terrace vary between 11 and 4 meters for the Galician side.
Field observations have shown that the Miño river level varies between 0 m a.s.l. close to the Atlantic to 5 m upstream of het fieldwork area. Thus, the variation between data points within a terrace level is greater than the variation of river gradient. Variation between field measurements for a given terrace can be attributed to a number of causes:

- Erosion
- Land use (gravel pits, mining, ploughing)
- Local sedimentation differences during terrace aggradation
- Differential tectonics (will be explained in Chapter 5)
- Measurement errors

Plotting a linear or exponential trend line through the data points is therefore not useful to calculate terrace height. After all, the calculated trend is dominated by the factors given above and *not* by downstream gradient. A second drawback of applying regression analysis is that the uncertainty R^2 cannot be calculated. The terrace profiles are lying on straight line with almost no gradient.
For this reason absolute terrace height is derived by calculating the mean of the data points per terrace level. Terrace height above river level is given by subtracting the mean river level (0 + 5)/2 =2.5 m from the mean value of each terrace level. Calculating mean values makes it also possible to give the standard deviation of the mean height of each terrace.
For T1 the minimum and maximum terrace heights were calculated as the terrace surface rises away from the river.

4.5.5 Distinguishing differential tectonics between both sides of the Miño

For the Galician and Portuguese side two different trend lines were used and compared. This made it possible to distinguish terrace height differences and consequently differences in uplift between the Portuguese and Galician side of the lower Miño.

4.6 Dating the fluvial terraces

4.6.1 Inventory of enclosures for sampling purposes

A collaboration was set up with geologists from the Instituto Universitario de Xeoloxia Isidro Parga Pondal of the University of A Coruña. They were willing to data terrace samples if I collected them. This meant that I was fully responsible for finding good enclosures. For this reason, I went to A Coruña prior to my fieldwork to learn what requirements sediments suitable for Optically Stimulated Luminescence (OSL) dating have. Such samples have certain requirements that were not easily met in the study area. The sediments should be of a medium to coarse sandy texture with sufficient quartz and/or feldspar minerals; these sands may not contain too much humic acids as they destroy the crystallinity of the minerals; and the sands may not be cemented by iron or other concretions. These sandy layers should be located close to the terrace base and surface to get a time window in which the terrace was aggradated. Layers too close to the base were not suitable as radiation emitted from the granite saprolite disturbs the reading of the quartz signal.
Because the terraces are lying on top of a deeply weathered bedrock mantle it was occasionally difficult to distinguish between sand from this mantle and fluvial sand. This problem was solved by looking at the composition of the weathered material as pieces of angular quartz were usually present. These form the residues of the weathered granitic bedrock, whereas fluvial sands contain rounded quartz.
It was very difficult to find suitable enclosures due to the presence of forest, vineyards and crop fields. Gravel pits and road works provided some good enclosures, but not enough to obtain samples for all terrace levels. The terraces themselves consist for the greater part of gravels and sand lenses are rare. For this reason, all sandy layers encountered were sampled, even if not of the best quality.

4.6.2 Sampling terraces for OSL-dating purposes

Three days were spent taking samples together with colleagues from the University of A Coruña. Samples were taken by inserting an aluminium shaft into a sandy layer using a sledge hammer, and placing the shaft in a light-proof bag after retrieval. In order to determine the start and end of terrace formation, samples were taken as close to the terrace base and surface as possible. We were very succesful in taking samples close to the base, but could not sample close to the terrace surface as all terraces contained at least a meter of gravel in the upper part of the terrace. All samples taken in the upper part are therefore at least one meter below terrace surface. Appendix 4 contains a list with details concerning the samples taken.

4.6.3 Preparation of samples for OSL-dating

I spent about 40 hours in the laboratory preparing various samples for OSL-dating. All preparations took place in an infrared illuminated room, as the samples may not be exposed to natural light. The samples were dried, sieved and separated into 5 different fractions. The 250-180µ and 180-90µ fractions were used for the dating process. These fractions underwent a number of treatments with chemical solutions to remove harmful elements. First, a HCl^- solution was applied to remove carbonates; then a hydroperoxide (H_2O_2) solution was applied to remove organic matter. After this micas and feldspars were removed as they interfere with reading the signal that the quartz is emitting. They were removed by hand and by passing the samples a number of times through a mortar and sieve. In this way, the softer micas and feldspars were effectively destroyed and removed from the sample. A last step was applying a mixture of hydrogen fluoride (HF) 10% and 20% and nitric acid (HNO_3) to remove feldspars. If the sample still contained feldspars and micas the procedure of manual removal and application of HF and HNO_3 was repeated as many times as needed. When the sample was found to be pure, the actual reading of the signal emitted by the quartz grains started.

4.6.4 Dating the samples with OSL-dating techniques

A number of fluvial samples were dated using quartz OSL-dating. After sedimentation, grains of quartz are buried, and consequently shielded from light. Surrounding sediments emit low-level ionizing radiation because of natural decay of mainly U, Th and ^{10}K elements. This radiation is trapped in the quartz grain lattices and builds up after time. When the quartz grain is exposed to light, this charge is released. This release happens in the form of a light flux which can be stimulated by heating a sample of quartz grains and read in a laboratory with OSL-equipment. The brightness of the luminescence signal is linked to the total charge built up in the grain since deposition (equivalent dose). The age can be determined by dividing the equivalent dose by the annual dose in the natural environment (Wallinga, 2002). To determine the equivalent dose a number of protocols has been been developed of which the singe-aliquot regenerative dose protocol (SAR-protocol) is the most widely used (Murray & Wintle, 2000). The laboratory in A Coruña also uses the SAR-protocol.
The maximum age that can be determined for fluvial sediments using quartz OSL-dating is around 150 ka, but this strongly depends on the saturation of the lattice traps in the quartz crystal (Wallinga, 2002). Recently, reliable older datings of fluvial sediments of up to 500 ka have been reported using the same method (Schokker et al., 2005).

See Chapter 5 for a more detailed description on equipment used and procedures in general.

Chapter 5 Results and discussion

5.1 Introduction

This part describes the fieldwork results and compares them with the work of earlier authors. This is not as straightforward as it seems. The first and most important problem that is that different authors use different reference levels to compare their terrace heights with. Some use mean sea level (m.s.l.) which in itself is a fairly reliable reference base, although its shape slightly differs for each geoid used. Notwithstanding that the usage of m.s.l. brings about a different kind of problem: terrace height above m.s.l increases upstream although terrace height above the river remains the same. Luckily, the study area is very close to the ocean and thus river level does not differ that much from sea level. This reduces the error when taking mean sea level as reference base and makes comparison still acceptable. Still, a relative reference level would be more convenient. Many authors revert to using relative height above river level and although this is a more reliable reference level, some problems still exist. The Miño water table rises and falls due to the proximity of the sea and seasonal discharge fluctuations. Also during the past decades the construction of dams and gravel mining have caused a lowering of the water table. A comparison with earlier work is therefore tentative.

Many authors have neglected to mention *what* exactly they are describing. Some describe for instance a terrace level at 4-9 m without mentioning what this means. Does this mean that the terrace surface varies from 4-9 m? Or does it mean that the terrace base is found at 4 m and the surface at 9 m? Some even forget to mention what reference level they use. It seems that all authors at least describe the terrace surface and therefore terrace surface height between works is analysed. Both surface altitude above mean sea level and above Miño river level is given.

5.2 Fieldwork results and comparison with earlier works on the Miño terraces

Figure 3 gives a complete overview of all villages and cities mentioned in the text below. Figure 4 shows all places where measurements were made that were used for profile reconstruction. The reconstructed terrace profiles are given in Figure 5. Table 1 gives the calculated mean and relative terrace heights and standard deviations. Table 2 compares the results with those from other workers in the fieldwork area.

Table 1. Calculated mean and relative terrace surface heights in meters and standard deviations in meters.

	Height (m.a.s.l)		**Height (river level)**		**Standard deviation**	
	G	P	G	P	G	P
T0	6.8	7.3	4.3	4.8	1.8	1.1
T1min	14.1	13.4	11.6	10.9	2.4	2.3
T1max	19.5	18.9	17	16.4	0.6	1.1
T2	24.2	24.5	21.7	22	1.7	0.6
T3	30.7	31	28.2	28.5	2.9	1
T4	40.7	40.1	38.2	37.6	2.2	1.9
T5	51.8	52.9	49.3	50.4	2.5	2
T6	66	66.5	63.5	64	1.7	1.8
T7	74.8	76.3	72.3	73.8	1	2.5
T8	86	84	83.5	81.5	1.4	n.a.
T9	n.a.	95	n.a.	92.5	n.a.	n.a.

G refers to Galicia
P refers to Portugal

In total 10 fluvial terraces were found. The youngest and lowest terrace is named T0 and the oldest and highest T9. The base of each terrace is found at the altitude where the lower terrace surface ends. The base of T2 is found where T1max ends as the T1 surface rises away from the river. For this reason the minimum and maximum height of T1 was measured. Table 1 shows that there is good agreement between terrace level heights on both sides of the river. Standard deviations for Galicia vary from 0.6 m for T1max to 2.9 m for T3. Deviations for Portugal vary from 0.6 m for T2 to 2.5 for T7. Those were not available for T8 and T9 as only one measurement was made. The Portuguese side has lower standard deviations compared to the Galician side for T0, T1min, T2, T3, T4 and T5. This can be attributed to better preserved terraces and more accurate measurements. After all, the Portuguese terraces were additionally measured with a high-precision altimeter whereas Galician terrace data was improved with a digital map with 5 m contour intervals. For this reason the Portuguese terrace levels are used as representative for the Miño terrace levels.

What follows next is a more elaborate description of field observations compared against existing literature.
The T0 surface is found at a mean level of 7.3 meters. It is not a flat surface but still rises away from the river. Calculated height above the Miño is 4.8 m. All authors mentioned agree with the general surface height of this level.
In the lower reach of the area the tides start to exert their influence and mud patches become a prominent feature in the landscape. These mud patches start to interfinger with the T0 terrace and consequently the T0 is getting a floodplain-like appearance. The distinction between T0 and the mud patches is therefore not very clear and may be a source for errors.

T1 is visible in the landscape as a very well developed, broad surface. In some areas like Tabagon it reaches an extent of several kilometres.wide and long. The terrace consists of unconsolidated material such as sands and gravel and is distinguished from the T0 by a clear scarp face. In Portugal the scarp forms a massive 4 m wall, but seems to be less pronounced in Galicia due to many excavations. T1 experiences a rising of the terrace surface away from the river from 13.4 to 18.9 m. a.s.l. This seems to be the main cause of the different heights found by various authors. Teixeira (1952; 1955; 1962) and Nonn (1967) find the terrace between 15 and 20 m. Cano-Pan et al. (1997) even find a range from 10-19 m, but it is not clear where this height refers to as they neglected to mention what part of the terrrace they are discussing. All in all, most authors agree with a minimum value of 15 m.a.s.l. and a maximum value of 20 m.a.s.l. for the terrace surface. This is in agreement with my findings, although my minimum value for the terrace surface is a bit lower at 13.4 m.

T2 is found at a few locations in the area but it is not a very well developed terrace and seems to be absent altogether upstream where instead a bedrock canyon is found. The terrace surface is located at a mean height above sea level of 24.5 m. The mean height above river level is 22 m.
In some areas the distinction between T2 and T3 is not clear as they seem to merge into one terrace, for instance around Vila Meã. In other areas like Caldelas and Barbeita there is a clear transition from T2 to T3. Teixeira et al. (1955; 1962) group this terrace together with the T1 level, although this seems incorrect as a clear transition from T1 and T2 is found in many areas, for instance in Lanhelas, Portela Conguedo and Ganfei. Butzer (1967) and Nonn (1967) share my findings as well as Cano-Pan et al. (1997). The latter places the terrace surface a bit higher at a maximum of 28 m. The other authors did not find this terrace level. This is not strange given its incomplete development.

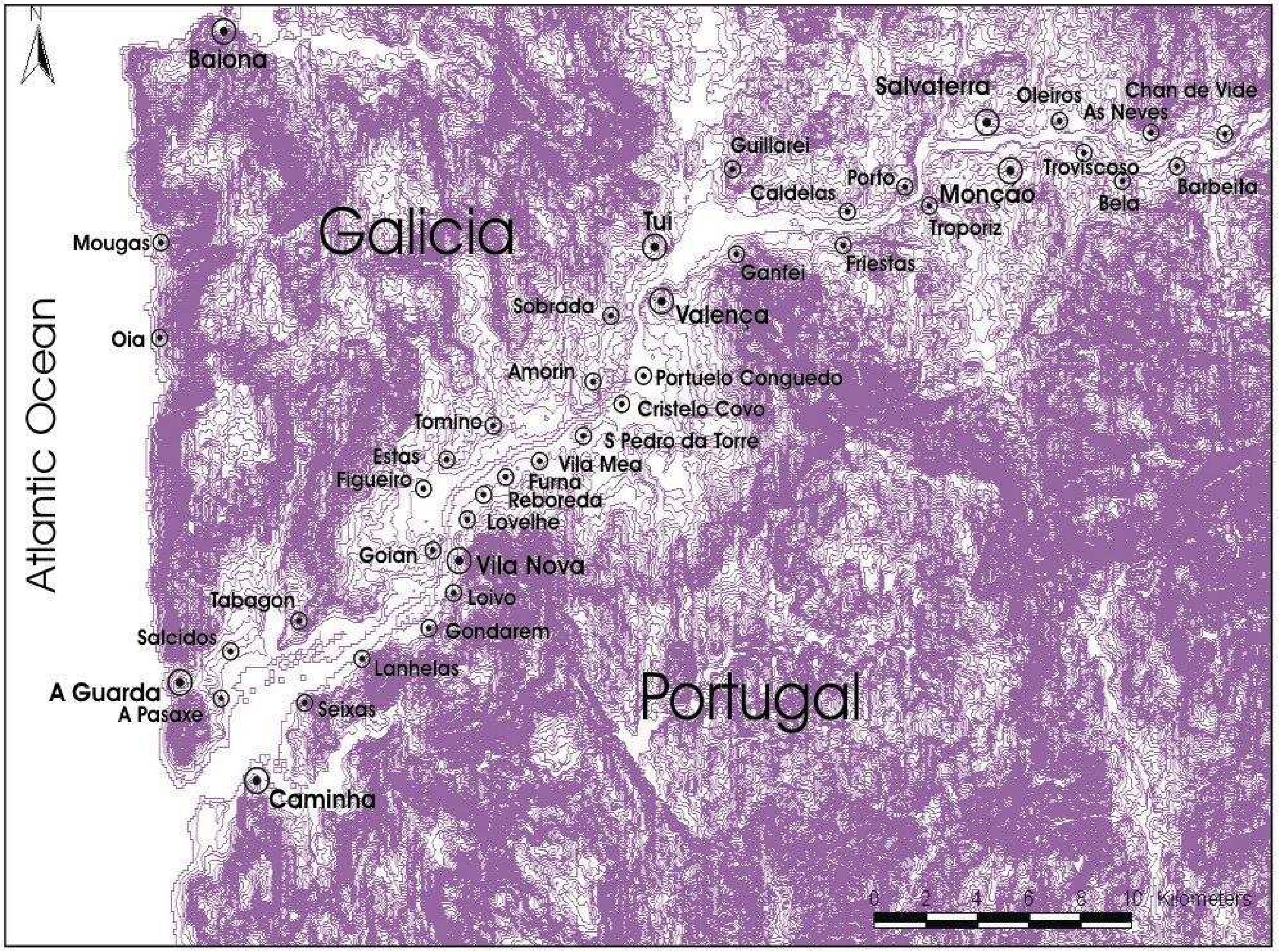

Figure 3. Topographical map of the fieldwork area. The Miño river shown in centre of picture flowing SW. Larger dots indicate cites and smaller dots villages. Purple contour lines with a 10 m interval. Highest point around 700 m.

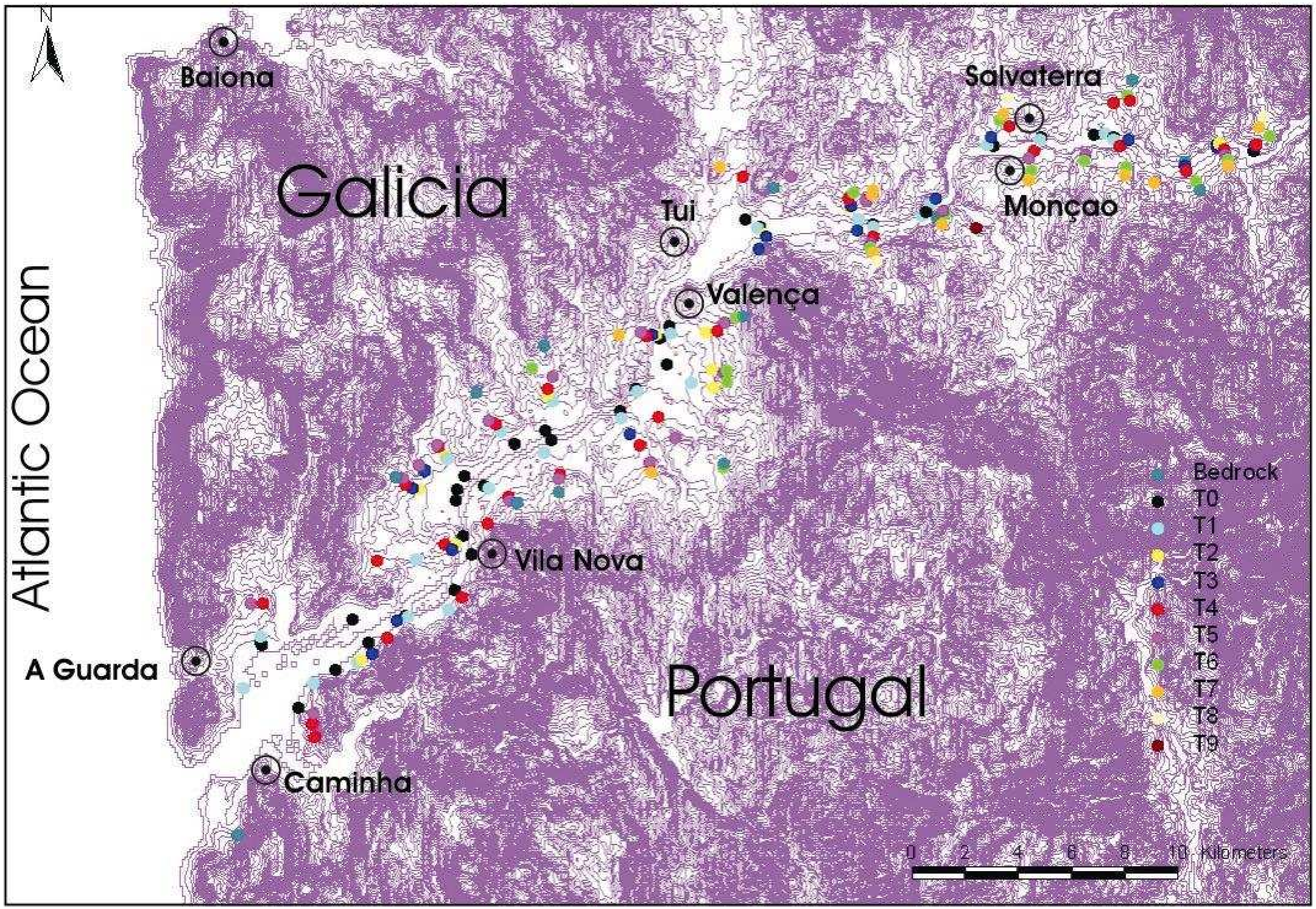

Figure 4. Map with places where valid terrace location and height measurements were made. Coloured dots indicate terrace levels.

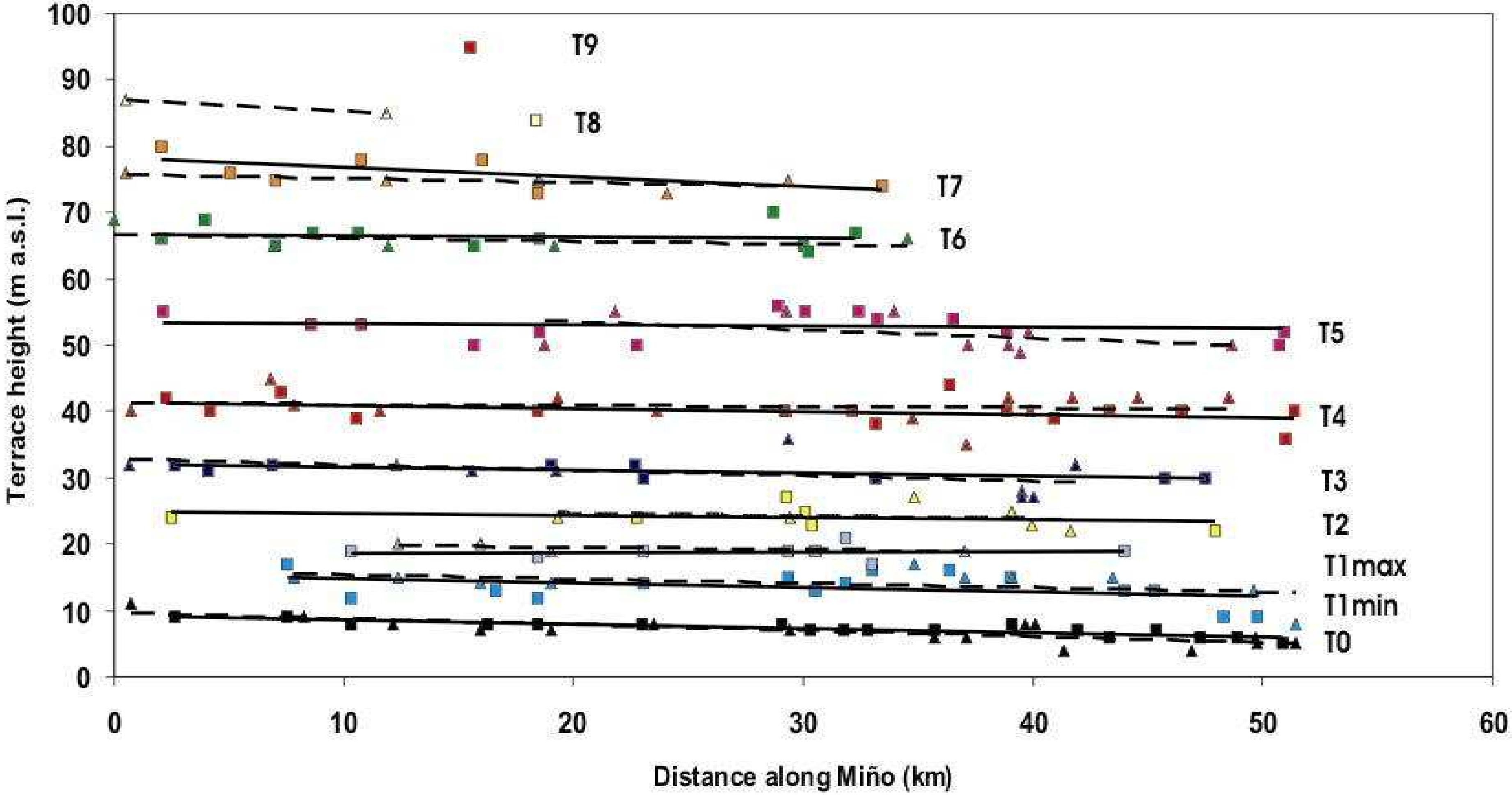

Figure 5. Reconstructed terrace surface profiles by means of linear interpolation. 0 km indicates beginning of fieldwork area and 52 km where Miño meets the Atlantic Ocean. Ten terrace levels visible (T0 to T9) with height given in meters above sea level. Solid lines and squares indicate Portuguese side of Miño and dashed lines and triangles of same colour indicate Galician side. Same colours used as in Figure 4.

Table 2. Earlier work on the lower Miño fluvial terraces compared with fieldwork results for Portuguese bank of Miño ("this work"). Three * indicates that no terrace level was found by the author.**

Author	Lautensach (1945)	Teixeira (1952)	Butzer (1967)	Nonn (1967)	Geological maps Spain 1:50,000*	Geological maps Portugal 1:50,000**	Cano-Pan et al. (1997)	Cano-Pan et al. (1999a)	Alves (2004)****	This work	
Area investigated	Cortegada-La Guardia (GP)	Melgaço-Caminha (P)	Porto-La Guardia (G)	Las Nieves-La Guardia (G)	Arbo-La Guardia (G)	Melgaço-Caminha (P)	Tuy-La Guardia (G)	Chan de Vide-Salvatierra (G)	Valença-S. Pedro da Torre (P)	Chan de Vide-La Guardia (GP)	
Reference level	River level	River level	Mean low water river	River level	Mean sea level	Mean sea level	Mean sea level?	Mean sea level?	Mean sea level (pers. comm)	Mean sea level	River level
Part of terrace described	Surface	Surface	Surface	Surface?	Surface?	Surface?	Base and surface?	Base and surface?	Surface	Surface	Surface
T0	5-10	5-12	3-10	***	0-10	5-8	2-9	5	5	7.3	4.8
T1min-max	20	15-20	***	15-20	***	15-20(25)	10-19	8-10	15	13.4-18.9	10.9-16.4
T2	***	***	22-24	25	10(13)-25(30)	***	19-28	***	***	24.5	22
T3	***	***	34-36	30-35	***	***	***	***	***	31	28.5
T4	40-45	30-40	42-44	35-45	30-45(50)	30-40(45)	32-42	30-40	45	40.1	37.6
T5	***	50	52-59	50-55	***	45-50(55)	42-55	***	55	52.9	50.4
T6	***	60-70	65-68	65	50(55)-70	60-70	52-62	69-75	***	66.5	64
T7	***	75-80	76-80	***	***	75-80	65-72	75-80	***	76.3	73.8
T8	***	***	***	***	***	***	***	80-90	***	84	81.5
T9	***	90-100	***	***	***	90-100	76-95	100	100	95	92.5

*****Rubio-Navas (1972); Abril-Hurtado (1972); Pliego-Dones et al. (1972).

******Teixeira et al. (1955; 1962).

********See also Pereira (1991); Alves & Pereira (2000).

P Refers to Portugal

G Refers to Galicia

T3 is one of the most clear terraces and can be followed almost continuously throughout the region. It has a flat terrace surface at 31 m a.s.l and a clear scarp. On both sides of the Miño the mean surface height is around 28 m above river level. Only Butzer (1967) and Nonn (1967) share my findings. The other authors argue that this terrace is part of the T4 level but this is definitely wrong. On numerous occasions a clear scarp face was found separating T3 and T4 for instance in Barbeita, Bela, Troviscoso, Friestas and Vila Meã. It is true that in some places a flat, slightly rising terrace surface exists between 30 and 40 m. I have encountered this as well in Cristelo Covo and Salvaterra and is likely the result of erosion or simply incomplete terrace formation. This example stresses the importance of doing thorough field investigation, especially in areas that are susceptible to erosion such as the lower Miño.

The next terrace T4 is also a very clear terrace with an obvious scarp face. It is perhaps the most complete terrace and can be found throughout the lower Miño. The terrace surface is found at 40.1 m.a.s.l. The mean altitude above river level is set at 37.6 m. In some occasions T3 and T4 merge together into one terrace and sometimes T4 follows directly on T2, showing a massive 20 m scarp face as is the case in São Pedro da Torre. Both cases are attributed to erosional forces and incomplete terrace development rather than differential tectonics.
All authors recognise this terrace level and there is consensus on a generalised height of 40 to 45 meters. Some workers consider a slightly higher value of 45 m but this value may reflect a local measurement. I myself as well have encountered values of around 44 m a.s.l for T4 (Reboreda, Oleiros) but they do not have a regional significance.

T5 is another gem of a terrace. It is found widespread in the region as a very large and extremely flat terrace surface, which can be hundreds of meters wide (Guillarei, Tomiño). Closer to the coast, it is the highest alluvial terrace found, as older levels are or eroded, or never existed at all. The terrace surface is found at 52.9 m above sea level. The mean terrace height above river level is 50.4 m. This is in agreement with the findings of all authors who also find 50-55 m values. Only Butzer (1967) finds a slightly higher value of 59 m in one of this transects and this affects his overall value for the area. His other surface heights are 52 m values, so we can safely say that there is consensus on the surface height of 50-55 m for T5.

T6 is present in a large part of the study area, albeit absent the last 15 km coastward. The terrace is quite eroded and in most cases a clean scarp face is no longer present. In Portugal the terrace is better preserved compared to Galicia. The lithology show signs of degradation in the form of soft, weathered quartz, quartzite and sandstone gravel and a significant increase in clay and loam in the matrix. The transition from T5 to T6 is clearly noteworthy as T5 has a very flat surface and a sudden increase in height means a transition to T6. In Salvaterra one of the best examples is found where the new motorway cuts right through this terrace. T6 does not have the well-developed extensive surface of the lower terraces and the transition to T7 follows quickly. The terrace surface is found at 66.5 m.a.s.l. This equals 64 m above river level. From this level onwards there is more disagreement between authors. Lautensach (1945) and Alves (2004) do not mention this terrace at all. Butzer (1967) and Nonn (1967) agree with my findings. The height values obtained by Cano-Pan et al. (1997) are slightly lower but still in agreement. Their values further upstream of 69-75 m (Cano-Pan et al., 1999a) do not fit and seem to be related to the T7 terrace.
The Spanish geological maps group this terrace level together with the T5 level and Teixeira (1952) and Teixeira et al. (1955; 1962) find values of 60 to 70 m. In some occasions surface heights of 69 m (Bela, Vide) and 70 m (Cristelo Covo) were observed during fieldwork, so Teixeira's observation of 70 m seems reasonable. His lower value of 60 m remains unclear though. In the study area the T6 terrace was found 16 times, so it is out of the question that this surface level does not exist. On numerous occasions clear transitions were found from T5 to T6 and from T6 to T7, indicating the existence of this terrace level as a separate level rather than part of T5. The height measurements are very consistent throughout the region

and backed by Butzer (1967), Nonn (1967) and to a certain extent Cano-Pan et al. (1997). There seems to be no reason to doubt the existence of this terrace level.

T7 is the last terrace with a regional extent and is found in the same areas where T6 is found. The terrace is in a very progressive state of degradation and a scarp face is no longer visible. A sudden rise in height marks the transition from T6 to T7. In the majority of occasions, the terrace surface is no longer a flat surface but forms a low isolated hill in the landscape. A notable exception is Chan de Vide where the terrace surface is still intact. Here the sample for OSL-dating was taken. The terrace surface is found at 76.3 m above sea level. In some occasions, the surface still rises away from the river and attains a maximum height of around 80 m. These findings are in line with observations of Teixeira (1952), Teixeira et al. (1955; 1962), Butzer (1967) and Cano-Pan et al. (1999a). Cano-Pan et al. (1997) find a level at 76-95 m, but further discussion will point out that this level can be divided in several terrace levels.

T8 hardly is present. Only in Portugal, a clear transition from T7 to T8 was found with a surface height of 84 m above sea level. At two other occasions in Galicia terrace heights of 87 and 85 m respectively were found. These at first were considered part of T7 (see appendix 2 measurement numbers 2 and 113) because a scarp face or a clear increase in height could no longer be discerned. However, after having created the terrace profiles it became clear that these heights did not fit the pattern of T7 and consequently had to be a new terrace level. Because of the few measurements, it is difficult to reconstruct a reliable surface height. This level has been described by Cano-Pan et al. (1999a) only, as a 80-90 m level on the Galician side around Salvaterra. They also found this level further downstream around Tuy as part of a terrace surface at 76-95 m (Cano-Pan et al. 1997). I found this level in Portugal downstream of Salvaterra but upstream of Tuy. This means that, although sparsely present, T8 has a regional distribution making it likely that the level represents a separate terrace.

T9 was found in one occasion only, but appeared to be in a prime state. A flat, broad surface of several hundreds of meters wide with plenty of sediment was found in Troporiz at an altitude of 95 m above sea level. It was reported (Cano-Pan et al., 1999a) that in Salvaterra another surface of similar height exists, but the maximum level I found there is 87 m. In Troporiz the terrace base followed directly from T7 but the T8 level has probably been eroded. T9 has been described by Teixeira (1952), Teixeira et al. (1955; 1962), Cano-Pan et al. (1997; 1999a) and Alves (2004). Some are in favour of a 100 m surface height and some of a 95 m surface height. The scarcity of observations makes it difficult to come up with a reliable regional level, but the one observation made is a very reliable one and in agreement with Cano-Pan et al. (1997). For this reason a mean surface terrace height of 95 m.a.s.l is proposed.

Generally, the results agree very well with the outcomes of earlier research. All terraces and terrace heights were recognised by other authors, but up till now no one has obtained a full set of terrace levels. This research is the first that proves the existence of ten terrace levels. The terrace levels can be connected to the levels upstream of the fieldwork area towards Melgaço as shown by the strong correlation with the works of Teixeira (1952), Rubio-Navas (1972), Abril-Hurtado (1972), Pliego-Dones et al. (1972) and Cano-Pan et al. (1999a). See Table 2. My research also stresses the importance of doing proper, regional-scale fieldwork to obtain a coherent view of the area. In this context, I would like to express my concern regarding the work of for instance Alves & Peireira (Alves & Pereira, 2000; Pereira & Alves, 2000; Alves, 2004). They investigated the terraces of only a small area in the lower Miño between Valença and São Pedro da Torre and concluded that the entire 80-km stretch of the lower Miño on both sides has five terrace levels. They proceed using this sequence to make comparisons with the other fluvial systems in the Portuguese Minho region and draw regional-scale conclusions that are not fully grounded in reality.

Another example is the earlier discussed work of Cano-Pan et al. (1997; 1999a). They mapped the entire area between La Guardia and Arbo and proceeded to write two articles. Those two articles show a clear disparity in the number of terraces and the height of the terrace surfaces encountered, but they do not mention this disparity let alone try to find the underlying reasons for it. This shows the need of doing proper fieldwork as a basis for further research.

5.3 Comparison of the fluvial terraces against marine terraces

Butzer (1967) found seven marine abrasion platforms in Galicia but due to the absence of sediments, he could not prove their relation to interglacial sea level high stands. The 44-49 m marine platform extends landwards north of La Guardia and connects directly to the Miño T4 fluvial terrace. According to Butzer this forms the only direct stratigraphical link between the fluvial and marine environment.

Meireles & Texier (2000) describe ten marine terraces for the Portuguese coast just south of the Miño river mouth. They found abrasion benches covered by marine sediments laid down in intertidal and supra tidal environments.

The existence of marine abrasion benches and in some cases fossil beach deposits has been confirmed by numerous authors (see Carvalho et al., 2006 and references therein) although there is some scepticism regarding the marine origin of the Galician abrasion platforms (Blanco-Chao, pers. comm; Vidal-Romani, pers. comm).

Table 3 compares these abrasion platforms or marine terraces with the alluvial terraces in the lower Miño. Although it is common practise to correlate marine terraces with fluvial terraces found near the outlet (see e.g. Merritts et al. 1994), care must be taken. Upstream of a river, terrace gradients may change, causing erroneous correlations (Merritts et al., 1994). Especially in the case of a backfilling sedimentary wedge, terrace gradients may differ. Overall, Table 3 shows that there is reasonable agreement between the fluvial and marine terraces. Butzer’s (1967) 2.5 m level is not found by the other autors and neither is my 73.8 m fluvial terrace. But overall, a certain agreement between terrace heights and spacing between levels is found.

The 10.9-16.4 m fluvial T1 terrace can be connected to the 10-12 m and 16-17 m levels of Butzer. Perhaps the T1 terrace consists of two separate terraces instead of one. This would explain the large height increase of this terrace. This cannot be confirmed on basis of the available fieldwork data and we will continue working with T1 being one terrace.

Table 3. Abrasion platforms and marine terraces in meters above sea level described by Butzer (1967) and Meireles & Texier (2000) compared against the lower Miño fluvial terraces in meters above river level. (G) refers to Galicia and (P) to Portugal.

Butzer (1967)	Meireles & Texier (2000)	This work (2008)
Baiona-A Guardia littoral (G)	Minho littoral (P)	Lower Miño (GP)
2,5	***	***
6-7	3-5	4.8
10-12	8-14	10.9-16.4
16-17	18-22	10.9-16.4?
23-24	25-27	22
33-36	31-36	28.4
44-49	41-45	37.6
***	48-54	50.4
***	63-67	64
***	***	73.8
***	80-88	81.5
***	100-140	92.5

5.4 Differential tectonics

Figure 5 shows the terrace profiles in the fieldwork area. First of all the figure shows that in general, measurements were made throughout the area, with the exception of T2. This terrace was hardly found in the upper 20 km section of the fieldwork area.
T6, T7, T8 and T9 are not found in the downstream section close to the coast. It is possible that during the time of terrace formation, the catchment was less developed and that the land-sea transition was found much further inland. As terraces cannot form under water, no terraces are found in Figure 5 between 35 km and 52 km.
Along the transect in between 23 and 29 km, no measurements were made. The city of Tuy is found here and the Louro river valley connects to the Miño valley, making fieldwork very hard. When we compare individual measurements before and after this gap, something strange is seen. After the gap, data points are situated a number of meters higher than the points along the transect upstream. This is especially clear for terraces T1min, T2, T3 and T5. Explanations could be better terrace preservation or measurement errors. On the other hand, there is a reason why the city of Tuy and the Louro river are found here: they are situated in the N-S running Depresion de Meridana, the largest fault line in NW Iberia. It is therefore possible that there are two tectonic blocks within the fieldwork area. Quaternary activity for the fault line has not been reported, but the striking height differences of data points within terrace levels béfore and after this fault cannot just be ignored. Especially not because both the Galician and Portuguese side register this sudden height increase. This renders the argument of terrace preservation and measurement errors rather unlikely. Still, stratigraphical analyses of terrace sediments on both sides of the Depresion de Meridana are needed to support this idea. For the moment, we will assume that the entire fieldwork area behaves as one tectonic block. This hardly has consequences for the reconstructed terrace profiles as height differences are minimal.

Figure 5 also shows that all profiles have a very low gradient and are running parallel to the youngest terrace (T0) indicating a synchronous uplift throughout the study area (Summerfield, 1991).

The most important finding is that there is no visible difference in terrace heights between Galicia and Portugal, but it is fair to mention that there is a theoretical measurement error of 5 m for the Galician terraces. This means that in theory there could be a height difference of 5 m for each Galician and Portuguese terrace level. However, Figure 5 shows no signs of unpaired terrace levels and measurements for the Galician bank do not differ significantly from those of the Portuguese bank. It is therefore safe to assume that there is no height difference between paired terraces. This means that both areas behave the same with respect to potential tectonic uplift. Either both sides are stable or both sides are uplifting. This contradicts the long-standing theory that Galicia is tectonically stable and Portugal uplifting (see e.g. Martin-Serrano, 1994b, 2005). This issue will be explored more thoroughly in the modelling exercise and a full discussion will follow later on. For the moment, we only have to keep in mind that both sides behave equally for the studied period.

5.5 OSL-dating results

As of yet, seven samples have been dated. See Table 4. The OSL-signal was near at or saturated for samples CDV1-2, ST1-2 and OL1. For this reason the ages in Table 4 for those samples are considered unreliable. Only a minimum age estimation of approximately 100-200 ka can be given, but for the moment the exact minimum age is still under discussion. See Appendix 6 Plates 4, 10 and 11 for impression of the ST-1 and CDV1-2 terraces.

The Chan de Vide 3 and 4 samples (see Appendix 6 Plate 3) give reliable ages of 0,15 ± 0,02 ka for the top and 1,22 ± 0,12 ka for the section halfway the enclosure. These are extremely young ages for such a terrace. As a matter of fact, there was already strong doubt whether this was a terrace or not. In favour of being a terrace was the transition visible to T2 and to T4; a large flat terrace surface at a height representative for this terrace level was present, and the geological map indicated that this was a terrace as well.
On the other hand, the sediment column consists entirely out of homogeneous medium to coarse sand with a high organic matter content which reminded more of Holocene sands than of pre-Holocene terrace material. In the end we decided to take samples for this terrace because it was the only enclosure available for the "T3 terrace". Combining the sample ages and the sedimentology, lead to the conclusion that this "terrace" is not a terrace. A more likely explanation is that it is slope-derived material generated by intensive deforestation in the catchment. Galicia has a long history of deforestation that started as early as 5000 years ago (Martinez-Cortizas et al., 2005).

Table 4. Dating results.

Code	Name & location	Terrace number	Age (ka)
CDV1	Chan de Vide 1	T7	144 ± 14,21
CDV2	Chan de Vide 2	T7	133,05 ± 14,85
CDV2 lixivated	Chan de Vide 2	T7	183,99 ± 20,00
CDV3	Chan de Vide 3	-	0,15 ± 0,02
CDV4	Chan de Vide 4	-	1,22 ± 0,12
ST1	Salvaterra 1	T6	506,25 ± 66,81
ST2	Salvaterra 2	T7	214,18 ± 21,71
OL1	Oleiros 1	T6	-

Chapter 6 Partial conclusion

In the lower Miño ten fluvial terrace levels are present (see Table 2). These fluvial terraces show a strong correlation in altitude and number with marine abrasion benches and marine terraces along the Galician-Portuguese coast. The fluvial terraces are found at the same altitude on both sides of the Miño river, indicating that there is no difference in potential uplift. Research has shown that Portugal experiences Quaternary uplift, which suggests that Galicia does so as well.
OSL tests indicated that the quartz OSL signal had reached saturation. For our samples this indicates a minimum age of 100-200 ka. Hence, quartz OSL dating could not provide information on the exact timing of deposition.

Part III

Modelling the Miño-Sil system dynamics

Chapter 7 Model input

The numerical model Fluver 2, developed by Veldkamp & Van Dijke (1998, 2000) will be used in this modelling exercise. The model was succesfully applied to a number of river systems in Western Europe such as the French Allier and Loire (Veldkamp & van Dijke, 1998), the Dutch/Belgian Meuse (Tebbens et al., 2000) and the Upper Aller in Northern Germany (Veldkamp et al., 2002). Recently, the Upper Thames in the United Kingdom was investigated by means of Fluver 2 (Stemerdink, 2007).
Fluver 2 is a model that describes "long-term fluvial processes relating sediment transport capacity of the fluvial system to discharge, topography and slope processes" (Tebbens et al., 2000). The model is capable of simulating where and when a river system will erode and aggradate, depending on the prevailing external (climate, sea level, tectonics) and internal conditions (discharge capacity, sediment supply).
Longitudinal profile changes (δx) are triggered by changes in relief (δz) through time (δt). They are a function of sediment flux changes (δfs) caused by erosion (E) and sedimentation (Sd) as proposed by Veldkamp & Van Dijke (1998):

$$\delta z/\delta t = \delta fs/\delta dx = E-Sd$$

The maximum amount of sediment (Qs) a river is able to transport depends on discharge (Qw) and slope of the river (S) as proposed by Kirkby (1971):

$$Qs = k * Qw * S^n$$

The factor k is related to sediment properties with a high value indicating easily movable sediments and a low factor indicates resistant sediments and bedrock.
The exponent n is a constant.

The altitude H is at a given time step (t) is a function of independent variables and H at time t-1 (Veldkamp & Van Dijke, 1998):

$$H_t = H_{t-1} + (Qs_{x-1} – Q_{sx}) * dt/dx$$

Fluver 2 does not use a 3-D structure such as a DEM to make space-related calculations. The core entity of a DEM, a gridcel, does not exist in Fluver 2. Instead, the model calculates in "steps". These are 1-D line features of a given length, that together form the longitudinal profile of a fluvial system. In our case the Miño-Sil longitudinal profile is made up of 1201 steps of 340 m each. The total length of the river system is 408 km, including the submarine part on the continental shelf.
For each 340 m step along the profile the model calculates the amount of erosion and sedimentation, depending on the current external and internal conditions. Timewise Fluver 2 calculates in phases of 20 years. So the model calculates in a time-dimension at a given point along the longitudinal profile. It remains a 2-D model as Fluver 2 cannot calculate what happens in terms of the width of a river. A fluvial system may be 10 km long and 100 m wide, but the latter is not accounted for in the model. To compensate for this lack of dimension, additional sub-catchment and hill slope sediment supply calculations can be made.
The modelling exercise covers a time-period of 800 ka. This period was chosen because the age obtained for the oldest alluvial terrace is approximately 800 ka (see Chapter 7.1.5). The time in between 800 ka and the age of the oldest terrace is used as an initialisation period for the model to stabilise.

What follows next is a description of the model input required for Fluver 2 and an overview of the modelling results. These are discussed in the subsequent discussion. The conclusion summarises important elements of Part I, II and III.

7.1 Uplift rates and terrace ages

This section starts with a short overview of the current knowledge concerning neotectonics and terrace ages. On basis of this information, a number of scenarios is presented dealing with different possible combinations of tectonic uplift and terrace ages. The section concludes with an explanation on how to reconstruct these uplift rates and ages.

7.1.1 Overview tectonic history

The dilemma of the existence of Quaternary uplift was already discussed in Part I. This section elaborates more on proposed uplift rates by various workers. Uplift rates for Northern Portugal exist, but are in general limited to the coastal areas. Granja (1999) proposes uplift rates of 3 mm/yr for the last 5.5 ka or 1.4 mm/yr for 3.5 to 3.2 ka for the Portuguese coast just south of O Porto. Cabral (1995) proposes uplift rates of 100 m at the coast to 300 m upstream for the past 2 to 3 Ma in the Portuguese lower Minho. This equivalents 0.033 to 0.05 mm/yr at the coast and 0.1 to 0.15 mm/yr upstream.
There is great controversy on the presence or absence of Quaternary tectonics in NW Spain and especially in Galicia. Since the early days of geological research, the region has been considered tectonically stable (cf. Martin-Serrano, 1994b, 2005). Fluvial terrace formation took place because Tertiary uplift was so strong that river incision could not keep up. Even nowadays rivers are incising to re-establish equilibrium, although no uplift takes place (Herail, 1984). Most authors agree with this idea, but recent geophysical research suggests that there is ongoing tectonic activity. The stress field generated by a combination of the Atlantic push ridge and collision of the African and Eurasian plates, causes ongoing deformation of NW Iberia (Cloetingh et al., 2005). The NW-directed Betic collision phase plays an important role as witnessed by the NE-SW trending structural highs and lows in NW Iberia. These include the NE-SW running rivers Miño, Lima and Cavada and the Galician rias. Deformation causes vertical Pliocene-Quaternary movements with a total rate of 50-60 m on the Western Cantabrian coast (Cloetingh et al., 2005). Research on the submerged Galician shelf confirms this idea (Muñoz et al., 2003).
Cotilla-Rodriguez & Cordoba-Barba (2003) extensively studied possible neotectonic movements for Galicia applying an integrated approach of geomorphologic and geophysical techniques. They found no Quaternary tectonic movement in the Galician interior and moderate movement in the northern and western Galician sectors. They detected strong Quaternary tectonic movement on the Galician/Portuguese border of the river Miño.
Research on river terraces has recently shown that fluvial terraces cannot form without tectonic uplift. Climate and base level change play an important role as they trigger the transition from sedimentation to incision, but they alone cannot form the typical flight of terraces (Maddy, 1997; Maddy et al., 2000; Bridgland et al., 2004).

7.1.2 Proposed fluvial terrace ages by other authors

The majority of workers on the Miño terraces agree that terrace aggradation occurred during interglacials and incision during glacials because of the presence of red fossilised palaeosols and fragipans in the upper part of the older terraces. These palaeosols were supposedly formed during warm and humid periods in the Lower to Middle Pleistocene (Teixeira, 1952; Nonn, 1967; Butzer, 1967; Perez-Alberti, 1978).
Sedimentological research indicates that the amount of quartz decreases with increasing terrace altitude and kaolinitic clays increase with altitude. This indicates a more intense weathering for the older terraces attributed to a warmer and more humid climate (Pereira, 1991). This leads Pereira (1991) to propose an age of Upper Pliocene to Lower Pleistocene for the highest terrace.
At São Pedro da Torre a fluvial/fluvio-lacustrine deposit with plant macrofossils was found. The inferred age of these fossils is Upper Pliocene to Lower Pleistocene (Alves, 2004 and

authors therein). Because the 80 m terrace is lying directly on top of this deposit, Alves (2004) proposes an age of Lower to Middle Pleistocene.

7.1.3 Inferred age for youngest marine terrace

The correlation with marine terraces and abrasion benches is another indication that the fluvial terraces were formed during interglacials. The Portuguese 100-140 m marine level could be Pliocene and the subsequently younger terraces could have formed during Quaternary sea level high stands (Meireles & Texier, 2000). Radiocarbon dating of an organic layer on top of the 3-5 m marine terrace gave > 42.370 year for this deposit (Carvalho & Granja, 1997). Overlying this deposit a cold-climate associated colluvium is found. This suggests that the underlying marine terrace originates from the Eemian (Meireles & Texier, 2000).
A deposit on top of a 2.8 m high Galician cobble beach was radiocarbon dated at 36 to 32 ka ago (Trenhaile et al., 1999). The fossil beach was consequently linked to the Eemian interglacial as it experienced a higher sea level than the Holocene. Additional radiocarbon datings overlying similar platforms along the Galician coast confirmed this idea. Other marine associated features as abandoned cliffs and abrasion platforms at the same height are found along the Galician coast, suggesting that the area has been tectonically and isostatically stable since at least the Eemian (Trenhaile et al., 1999; Blanco-Chao et al., 2002; 2003).
The latest addition to these findings comes from the hands of Alonso & Pages (2007). They were able to date the colluvia overlying the supposedly Eemian abrasion platforms (at 1.5-3.5 m.a.m.s.l.) with OSL-dating techniques and obtained maximum ages of 70 ka for these colluvia. This further strengthens the idea that the abrasion platform is of Eemian age and that the Galician coast has been stable since at least MIS 5e.

7.1.4 Terrace age/uplift scenarios

To overcome this problem of conflicting information a number of scenarios is reconstructed. Each scenario takes different uplift rates into account. These scenarios constitute the basis for further exploration of the Miño and Sil system dynamics with the model Fluver 2. A number of assumptions is made and a number of rules is set:

- Initially it was assumed that the entire Miño-Sil system experiences the same uplift rate synchronously. The calibration procedure (Chapter 8) showed that this was not the case. Therefore, three tectonic blocks with different uplift rates are incorporated: the Cantabrian hinterland, the Bierzo and Galicia.
- The system is in a state of semi-equilibrium. This means that incision can keep up with uplift.
- For scenarios 1, 2 and 3 uplift is calculated by means of an uplift curve based on the Miño terrace flight (see 7.1.5).
- For scenario 4 uplift is calculated by means of a marine terrace sequence.

7.1.4.1 Scenario 0: No uplift

No uplift for the entire Miño-Sil system. This scenario will test the prevailing idea that Galicia is tectonically stable. If so, then fluvial terraces should be able to form without uplift as proposed by Herail (1984) and Martin-Serrano (2005).

7.1.4.2 Scenario 1a and 1b: T0 linked to the Holocene

Terraces formed during interglacial aggradation and glacial incision.

1a. Aggradation of the T0 terrace is set at the Holocene. Uplift rates are calculated by means of the uplift curve.

2b. Aggradation of T0 set at Holocene. A mean uplift rate is calculated over the entire time-period.

7.1.4.3 Scenario 2: T0 linked to the Eemian

- Terraces formed during interglacial aggradation and glacial incision.
- Aggradation of T0 is set at the Eemian (MIS 5e). This means that the current Miño river bed is a Holocene terrace under construction.

7.1.4.4 Scenario 3: Terrace aggradation during glacials

The literature review showed that the terraces are most likely formed during interglacials. In theory, it is also possible that they were formed during glacials. The Meuse terraces are an example of glacial terraces (Van Den Berg, 1996). This scenario explores the possibility of glacial aggradation. T0 is for this reason linked to the Weichselian glacial.

7.1.4.5 Scenario 4: Marine terraces

For this scenario, no fluvial terrace sequences are used for uplift rate reconstruction. Instead, the marine terrace sequence as described by Meireles & Texier (2000) is used. This scenario takes into account that from the Eemian until the Holocene the area has been tectonically stable.

7.1.5 Reconstructing terrace ages and uplift rates

The uplift rates previously discussed in Chapter 7.1.1 cannot be used as they are too general. Therefore, we will have to resort to another approach. Usage of fluvial terrace sequences is an acceptable way to determine uplift rates (Maddy 1997, 1998; Maddy et al., 2000), but this should be done with great caution (Kiden & Törnqvist, 1998). Maddy (1997) proposes five assumptions that are critical to usage of a terrace flight for crustal movement reconstruction:

1. “The terraces considered in the model are the result of extrinsic variable change,
2. Terracing is not the result of eustatic change,
3. Terrace relationships are relatively unaffected by glacio-isostatic adjustments,
4. The river has responded uniformly within the study basin to external change,
5. Terrace height is a function of uplift resulting from the interaction of tectonic uplift and erosion-driven isostatic uplift.”

The first remark is a logical assumption as climate, base level and tectonics are considered to be the main players in shaping a landscape. As discussed, the terraces in the lower Miño can be correlated to possible marine platforms and it is therefore possible that eustatic changes were key to terrace formation. This matter is explored more fully in the modelling exercise.
The role of glacio-isostatic adjustments in Iberia is still under discussion. Glaciers have been present, but it remains unclear if they had sufficient weight to cause a significant lowering of the crust.
Assumption 4 seems valid as will be explained later on in this Chapter. The last assumption seems applicable as well. The region is very mountainous with steep slopes and has a humid and temperate climate favouring rapid erosion. In neighbouring Asturias with its comparable climate, sediment loss due to erosion started renewed isostatic uplift (Marquinez, 1992).

To use the Miño terrace flight for uplift reconstruction, we need to know if the longitudinal river profile was affected by differential tectonics during the studied period. Reconstruction of block movement has proven to be impossible as the area is lacking in sediments (Vidal-Romani, 1989; Martin-Serrano, 2005). To overcome this problem Yepes-Temiño (2002) correlated all terrace levels (both alluvial and strath terraces) of the Miño-Sil in Galicia. He used similarities in altitude to correlate terrace levels. This means that, in the absence of age estimations, the correlations remain tentative. Up to twenty terraces were found for the Sil and up to sixteen for the Miño extending up to 600 m above current river plain. The Miño and Sil have been down cutting consistently into the bedrock and all terrace levels can be followed throughout the valleys on the same altitude parallel above river level. This indicates the absence of individual block movement in Galicia.

Table 5. Overview terrace surface levels in the entire Miño-Sil catchment. Left side of Table starts with terraces most upstream (Leonese mountains). The more to the right in the table, more downstream terraces are found. Terrace sequence of this work (2008) was used to link terraces of other workers. Strath terraces above 100 m as described by Yepes-Temiño are not given. Terras chronology used by Yepes-Temiño was maintained to keep correlations between his work consistent. He rounded off his values to tens, which may be cause to a certain variation in altitudinal correlation. “ * ” indicates that no matching terrace level was found. All terraces are alluvial terraces. “e” indicates erosive/strath terrace.**

	Leonese mount.	**Bierzo**			**Galicia**								
Author	**Garcia-De Celis (1997)**	**Garcia-De Celis (1997)**	**Herail (1984)**	**Vidal-Box (1941)**	**Hernandez -Pacheco (1949)**	**Yepes-Temiño (2002)**	**Yepes-Temiño (2002)**	**Yepes-Temiño (2002)**	**Yepes-Temiño (2002)**	**Yepes-Temiño (2002)**	**Perez-Alberti (1978)**	**Yepes-Temiño (2002)**	**This work (2008)**
Area	Fosa de Paramo (Alto Sil)	Basin of Noceda	Bierzo	Bierzo and Valdeorras	Sil (entire Galicia)	Carucedo-Montefurado	Montefurado-rio Lor	Rio Lor-Miño	Portomarin -Os Peares	Os Peares-Ribadavia	Ribadavia -Quelle	Ribadavia -As Neves	Lower Miño
T0	5-10	5-10	5-10	5	4-6	0-40	0/80	0/10e	***	0	4-10	0	4.8
T1	20	20	15-25	10-12	10-12	20	***	***	***	10	***	20	10.9-17.4
T2	***	***	***	***	***	***	***	***	***	***	20-26	***	22
T3	***	***	***	25-30	25-30	***	***	***	***	30	30-33	***	28.5
T4	***	***	35-40	***	35-40	40/60	***	40/60^{e}	***	***	40-46	40	37.6
T5	60	50	***	***	60	***	***	***	***	50	***	60^{e}	50.4
T6	***	***	***	***	***	***	***	***	***	***	***	***	64
T7	***	80	70-80	***	70-100	80	80/100	***	***	70^{e}	***	70/80^{e}	73.8
T8	***	***	***	***	***	***	***	***	***	***	***	***	81.5
T9	100	***	***	***	***	***	***	***	100e	90e	***	100-120^{e}	92.5

Presence of lateral block movements in the Sil valley has been demonstrated for the oldest strath terraces (Yepes-Temiño, 2002) but this is not relevant for our study. This means that uplift rates inferred from terrace levels in a certain area can be applied to the entire longitudinal profile. In doing so, the assumption is made that terrace correlations made using only height as a criterium are reliable.
To check Yepes-Temiño's assumption previous work on the Miño and Sil terraces was collected and reviewed all over again. Work on the Leonese terraces of the Sil is added as well. Table 5 shows that in general terrace levels indeed maintain the same height above river plain throughout Galicia and to a certain extent in the Bierzo as well. Sometimes levels are missing, but this could be attributed to erosion. The closer to the coast, the more terraces are present. This could be a matter of preservation or a more sensitive registration of sea level fluctuations. The table also shows how much terraces are still present. This data is later on compared against the outcomes of the simulation exercise (Chapters 9 and 10).

Andeweg (2002) suggests that the Bierzo basin is subsiding relative to the neighbouring Douro. He argues that the base of the Douro and Bierzo basins can be correlated, but that the Bierzo base is situated 600 m lower. Andeweg speculates that the Bierzo is also subsiding in an absolute sense, although it is unclear if this process is still ongoing (Andeweg, pers. comm).
The Bierzo and sub-basins contain fluvial terraces, but Bridgland & Maddy (2002) argue that terraces cannot form in a subsiding setting. This seems contradicting. As the aim of this thesis is not to decipher the Bierzo tectonic regime, the middle road is chosen. The Bierzo is set at zero movement: no uplift and no subsidence.

For the upstream part of the Sil in the Leonese mountains, the same uplift rates as for Galicia were applied. It was assumed that the terrace levels of Paramo do Sil and the basin of Noceda (Garcia-De Celis, 1997) could be correlated to terraces of the same height in the Bierzo and Galicia. During the calibration procedure this turned out to be a false assumption and uplift rates were set at 0.3 m/ka. This will be explained more fully in Chapter 8.

Now that the usage of fluvial terraces has been justified, we can continue discussing how exactly to use the flight of fluvial terraces. Because the terrace flight in the fieldwork area is the most detailed one (see Table 5) we will use it for uplift and age reconstruction. Terraces T8 and T9 are of a very local extent and will not be used. T7 represents the oldest terrace and its age is the maximum age of the Miño-Sil system in the modelling exercise. To determine terrace ages, correlation to glacial/interglacial periods using a deep sea core is proposed. A glacial/interglacial regime seems appropriate because of the link with marine terraces and the prevailing idea that these terraces were formed under such a regime.
For global correlation, Bridgland & Maddy (2002) propose to use ODP core 677. In my opinion, currently a better correlation framework is available. Lisiecki & Raymo (2005) provide a stack of 57 globally distributed marine cores set on a new time-scale with MIS boundaries set halfway halfway a peak in $d^{18}O$. Their stack is also used for palaeodischarge and sea level reconstruction (Chapters 7.4 and 7.5). Linking terrace ages to this record prevents problems related to usage of different timescales.
It is worth mentioning that the vegetation record of NW Iberia shows that timing of most climate transitions of the past 430 ka was slightly out of phase with the marine record (Desprat, 2005). Sanchez-Goñi et al. (1999) and Shackleton et al. (2003) showed for instance that the Eemian in NW Iberia is not entirely in phase with MIS 5e, perfectly illustrating the limitations of global correlation. To keep the modelling time-framework robust, the MIS boundaries were not changed.

To calculate uplift rates by means of fluvial terraces, an uplift curve is reconstructed (Figure 6). Fluvial terrace surface heights above Miño river level are set out against each interglacial period (scenarios 1 and 2) or each glacial period (scenario 3). In the case of scenario 4 marine terraces are linked to interglacial sea level high stands (see Figure 8). The timing of

terrace aggradation is set halfway an (inter)glacial. For instance, time boundaries for MIS 5e are set at 123 ka and 109 ka respectively. The terrace is then linked to (123+109)/2 = 116 ka.
Uplift rates are calculated by dividing the difference in terrace height by the time difference between these terraces. If the curve displays a straight line in between terrace levels, it means that uplift is more or less constant. In this case, uplift over a greater time interval can be calculated and the error in uplift rate decreases. For instance, Figure 6 shows that the curve for the marine terrace scenario lies on a straight line for the four terraces in between 116 ka and 400 ka. Uplift rate is then calculated as difference in terrace height / time span. This equals (25-0)/ (400-116) =0.088 m/ka.

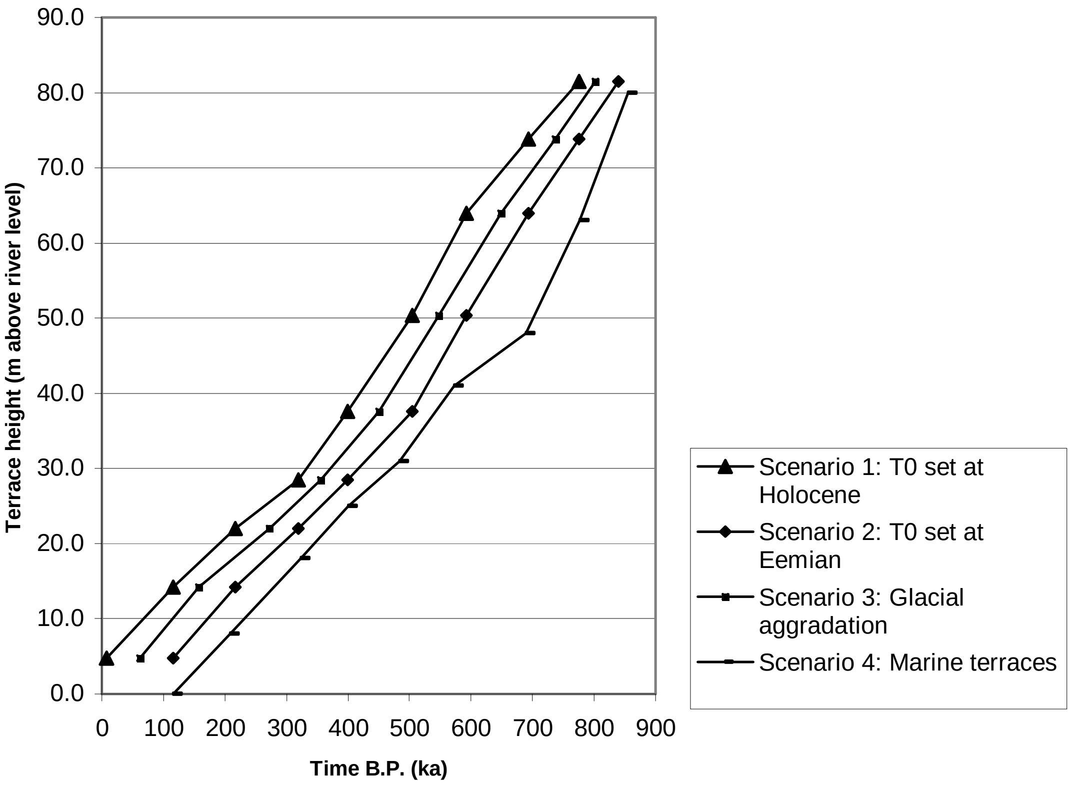

Figure 6. Uplift curve for scenarios 1 to 4. Symbols indicate terrace levels. The T7 terrace is not exactly set at 800 ka. For this reason T8 (80 m terrace) was used to interpolate to 800 ka. T8 is not part of the modelling exercise because in most cases it is formed before 800 ka BP.

In some cases an extra manipulation was needed to obtain correct uplift rates:

1. The youngest marine terrace at 116 ka is in reality found at 3 m a.m.s.l and not at 0 m as Figure 6 suggests. These three meters are the result of a higher sea level during the Eemian and not because of tectonic uplift. Various workers have pointed out that the Galician coast has been stable from the Eemian until now (e.g. Trenhaile et al., 1999). In order to calculate a correct uplift rate for the period 116-400 ka, the 116 ka terrace had to be set at 0 m.
2. Fieldwork has demonstrated that the terrace surface of T1 rises away from the terrace scarp up to several meters difference. For uplift calculations, the surface height of T1 is therefore set halfway the minimum and maximum terrace surface height.
3. In the scenarios where T0 is linked to MIS 5e and T0 is linked to MIS 2-5d, a graphical linear interpolation of the uplift rate from these periods to the Holocene was made.

Just like the terrace profiles experience a certain inaccuracy (depicted by the standard deviation), so do the uplift rates. After all, they are based on terrace height differences. To get an idea of this variation, the minimum and maximum variation in uplift rate for a given set of terraces was calculated. For example, for scenario 1 we would like to know the uplift variation for the period 217-319 ka. This period is represented by the difference of T2 at 22 m (relative to river) and T3 at 28.5 m. We know that the standard deviation for T2 is 0.6 m and for T3 1 m (see Table 1).
The smallest variation in uplift rate is calculated by taking the minimum distance between T2 and T3: 22+0.6 = 22.6 and 28.5–1 = 27.5. Subtracting 22.6 from 27.5 yields 4.9 m. This is the lowest total uplift possible.
The maximum uplift is calculated by taking the maximum distance between T2 and T3. These are 22-0.6 = 21.4 and 28.5+1 = 29.5. Subtraction yields 29.5-21.4 =8.1 m. This is the maximum total uplift possible.
The averaged uplift is 28.5-22 = 6.5 m. Both the minimum and maximum uplift have a variation of 1.6 m. This 1.6 m then has to be recalculated to a rate of m/ka.
Figure 7 gives the calculated uplift rates and variations for each scenario.

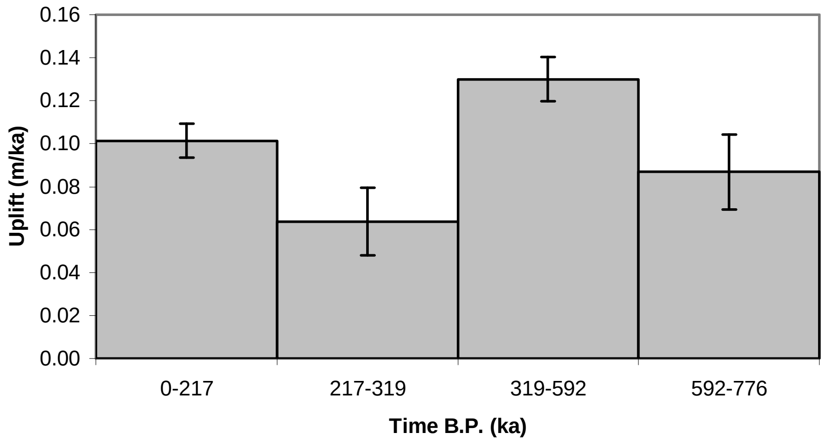

Figure 7a. Uplift rates for scenario 1a. Uplift rate in m/ka on Y-axis and time intervals on X-axis. Minimum and maximum variation in uplift rate is given by error bars.

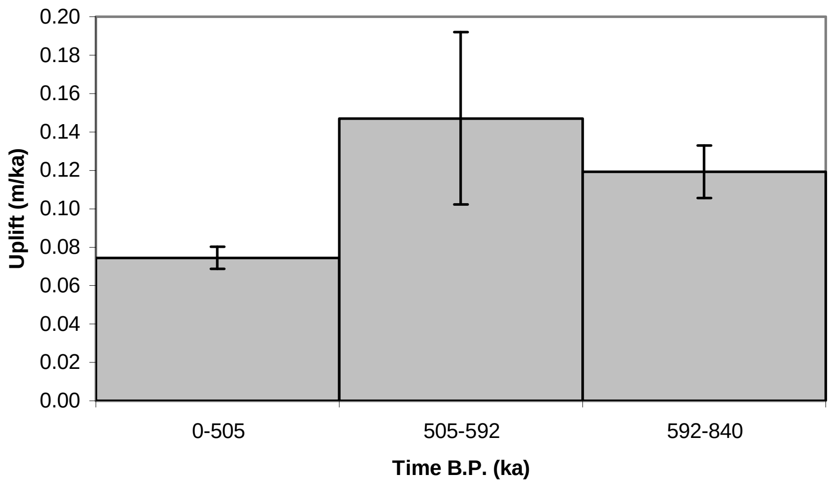

Figure 7b. Uplift rates and variation for scenario 2.

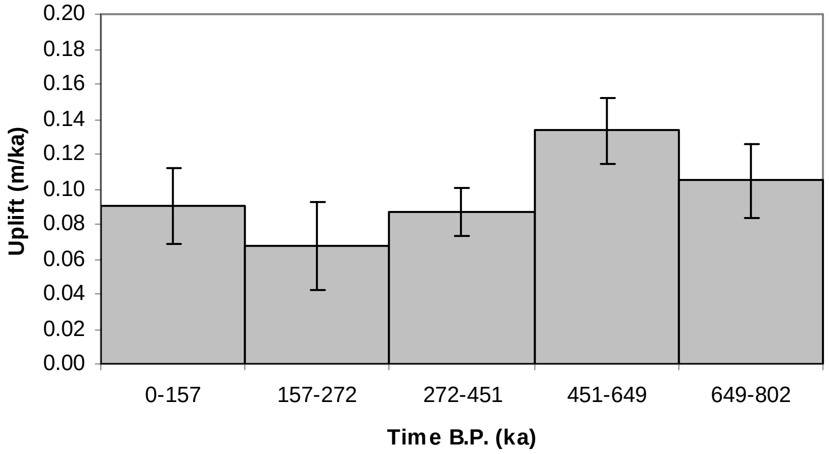

Figure 7c. Uplift rates and variation for scenario 3.

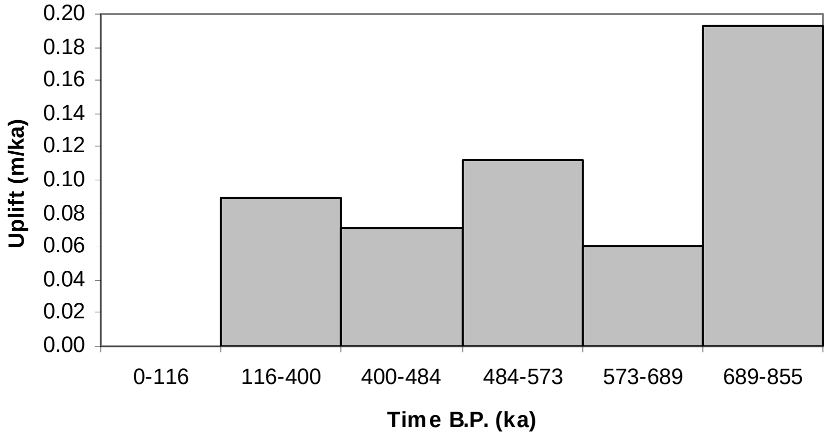

Figure 7d. Uplift rates for scenario 4. Uplift for 0-116 ka is 0 m. Because this scenario is based on existing literature, standard deviations could not be calculated. Hence, uplift rate variations cannot be given.

7.2 River captures

Head ward erosion caused the Sil to capture a number of tributaries in the mountains of Leon, where its headwaters are located. This headward erosion reached the western part of the basin of Laciana during the Tertiary-Quaternary transition. The tributaries of the Luna and Omaña rivers in the eastern part of the basin were captured during a longer time-span covering the greater part of the Quaternary and consequently had more time to deepen and expand the fluvial net. Head ward erosion in the headwaters of the river Boeza also occurred during the Quaternary but its precise history is difficult to reconstruct (Garcia-De Celis, 1997).

Yepes-Temiño (2002) describes a great number of river captures by the Miño and Sil rivers from the Galician/Leonese border up to the lower reach of the Miño. the Sil captured the headwaters of the Bibei, Cabrera, Xares and Mao rivers as well as the rivers Lor, Bubal, Camba, Ribeira and Conso; the Miño captured the rivers Sardiñeira, Saviñao and Arnoia and the headwaters of the Lonia and Barbaña rivers. In turn, these smaller rivers also captured a significant number of tributaries. The Arnoia captured for instance the Tamega river and the river Bibei the Navea and Larouco rivers. All these river captures took place before the Miño and Sil started to incise in the bedrock surfaces hundreds of meters above their current river plains. The current course of the Miño and Sil and their confluence was also defined before incision of these bedrock surfaces (Yepes-Temiño, 2002).
The Miño-Sil fluvial system is thought to be a very old system. Absolute datings are not available, but it is estimated that the origin of the system can be situated at least in the Paleogene (Vidal-Romani & Yepes-Temiño, 2001). The Miño and Sil are deeply incised in the bedrock as a result of epigenesis and in many cases their meandering forms can be found having cut out in hundreds of meters of bedrock. The river's direction is mainly dictated by the presence of fault lines.
All this makes that the current outline of the Miño and Sil drainage network has been laid out long before the current 80 m high flight of alluvial terraces came into being. It is therefore not unreasonable to assume that during the past 700 to 800 ka hardly any new river captures took place and that catchment size remained more or less constant. The aforementioned captures in the headwaters of the Sil can be neglected as they comprise only a very small area in the total Miño-Sil catchment.

7.3 Initial longitudinal profile

The DEM was used to derive a contemporary longitudinal profile for the Miño-Sil system. The longitudinal profile originally depicted two unnaturally steep slopes which turned out to be the the artificial lakes of San Estevo and Barcena. These corners were smoothed to obtain a more natural profile.
For the currently submarine part of the Miño no such data is available and hence, we have to make assumptions. The continental shelf is very narrow and adds therefore only 30 km to the total river length. A bathymetry map of the Galicia-Miño shelf (Dias et al., 2002a) was used to construct this submarine part by setting the current elevation of the seabed as longitudinal profile height. This is of course a simplification as the Miño sediments are no longer found on the seabed. Northward running currents move the fluvial sediment to the Galicia Mud Patch (Dias et al., 2002a).

To start a model run we also need to have an initial situation, that is, how the longitudinal river profile looked like 800 ka ago. The Miño-Sil is a very old system and it is therefore not illogical to assume that it has retained a state of quasi-equilibrium. This idea is confirmed by Yepes-Temiño (2002) and Yepes-Temiño & Vidal-Romani (2004) who found signs of antecedence in the area. Also, meander forms can be found cut out in the underlying bedrock as shown by numerous aerial photographs and satellite images. In the downstream reach of the Miño, the bedrock underlying the alluvial terraces has also been partly incised

by the river (Alves, 2004). These signs of epigenesis and antecedence indicate that incision could keep track with uplift and that the current profile will have more or less the same shape as the profile 800 ka ago. The profile in itself has a concave shape, which is also an indicator of a profile in quasi-equilibrium (Bull, 1991). If incision could keep pace with uplift, the current height of the profile will also be the same as 800 ka ago.
These ideas can of course not be applied to scenario 0, because this is a scenario without uplift. This scenario investigates the idea that fluvial terraces were formed by down cutting only. In other words, the initial profile should be set at a higher altitude than the current profile. In the fieldwork area the T7 terrace is found at a mean altitude of 73.8 m above river level and T8 (although scarcely present) at 81.5 m. The summary in Table 5 indicates that throughout the river system, alluvial terraces are found up to 70 to 80 m altitude. I assume that these terraces correspond in age and therefore the initial profile can be set at ~80 m above the current profile.
For scenario 0, the submarine part is not placed 80 m above current riverbed. The reason is that the area is submerged the greater part of time and erosion is therefore restricted. Figure 8 shows the initial profile reconstructions.

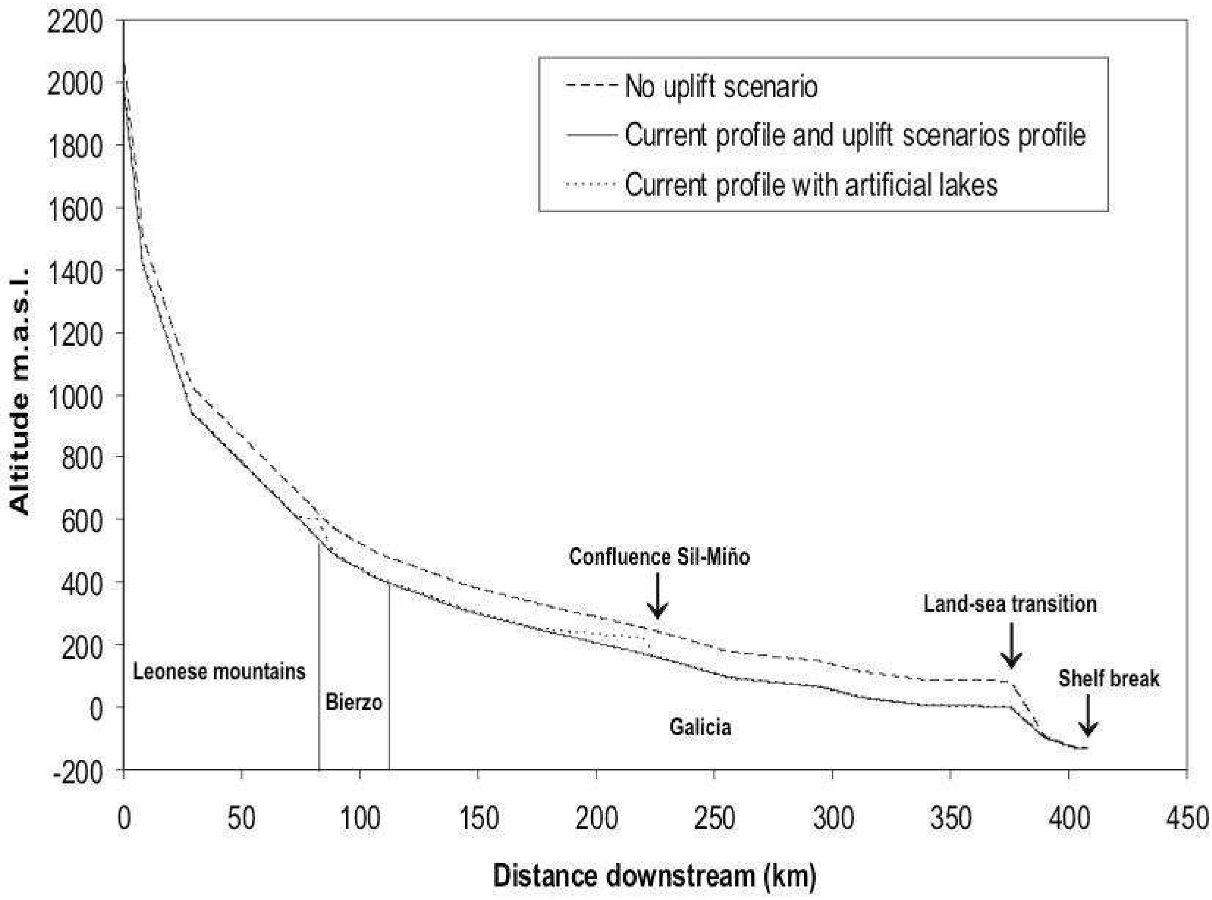

Figure 8. Initial profiles for the scenarios with no uplift and uplift (both fluvial and marine terrace scenarios). The original profile with artificial lakes is also given. These lakes were removed for the model runs.

7.4 Palaeodischarge and sediment supply

7.4.1 Proxy development

Time-continuous records on palaeodischarge and palaeosediment supply for the Miño-Sil system do not exist, even though the Iberian Atlantic margin is a key research area for palaeo-climate oriented research (Moreno et al., 2002). Long-term reconstructions of sea surface temperatures (e.g. Boessenkool et al., 2001), vegetation responses to climatic change and more are widely available. For this reason, scientists working on landscape modelling have used proxies to simulate palaeodischarges. Veldkamp & Van Dijke (1998, 2000) for instance have used the reoccurring pattern of the Milankovitch cycles as a proxy. This pattern can be used to predict changes in discharge and sediment load by assuming a linear correlation between caloric insolation, mean discharge and sediment supply. The three cycles of eccentricity (100 ka), obliquity (41 ka) and precession (23 ka) can be simulated by three mathematical sinus-functions, and combined in a single sinus-function to calculate effective precipitation. The initial input is current precipitation. The obtained effective precipitation is then linked to catchment size to calculate discharge over time (Veldkamp & Van Dijke, 2000).

Tebbens et al. (2000) used the $d^{18}O$-isotope values of the GRIP ice-core at Greenland to simulate discharge dynamics. The GRIP core basically registers temperature variations on the Greenland icecap and thus cannot be used directly as a discharge proxy. But it can be used in an indirect way. During glacials the huge quantity of water stored in the ice caps causes a high pressure area which pushes the depression tracks further south causing a drier climate with lower discharge rates in NW Europe. As these changes are reflected in the GRIP core, they can be used as a means to simulate relative changes in discharge rates.

Stemerdink (2007) used Sea Surface Temperature (SST) of the North Atlantic Ocean as a proxy for palaeodischarge because of the strong link between Holocene SST changes and precipitation changes. Stemerdink argues in his dissertation that this proxy is not the best proxy available. Also, the last two climate cycles off the Iberian shelf show sudden drops in sea surface temperatures. These drops are most likely caused by sudden iceberg discharges and do not correspond to the maximum extension of ice sheets (De Abreu et al., 2003) . This means that oscillations in SST cannot be used as a proxy for NW Iberian precipitation changes.

In this thesis, a similar approach as the one by Tebbens et al. (2000) is used for palaeodischarge calculations. But instead of the GRIP-curve, a marine oxygen isotope record is used. The GRIP-curve only extends back ~250 ka whereas this research focuses on a 800 ka time-scale. Several long-term deep sea records are available of which the ones taken in the Northern Atlantic Ocean would be the logical choice. DSDP core 607 would be most suitable as it is taken at the same latitude and in upwind direction of NW Iberia. Winds and currents coming from this direction directly dictate precipitation patterns and rates in NW Iberia, meaning that precipitation changes in NW Iberia will most likely be registered in the deep sea sediments where core 607 was taken. Unfortunately, the spreadsheet containing the data contains many errors and the time interval between subsequent measurements is not equal, something that is necessary for the model to run smoothly.
Therefore the choice was made to use the data of Lisiecki & Raymo (2005). They use a stack of 57 globally distributed marine cores (of which the majority comes from the Atlantic Ocean) and their data contains a fixed time-interval of 1 ka over the past 800 ka. Their data was compared against the data from DSDP core 607 and found to match quite well in most cases, making it a suitable proxy. Another advantage is that their data is in line with the sea level data of Bintanja et al. (2005). This is explained in Chapter 7.5. See Figure 9 for climate and sea level curve.

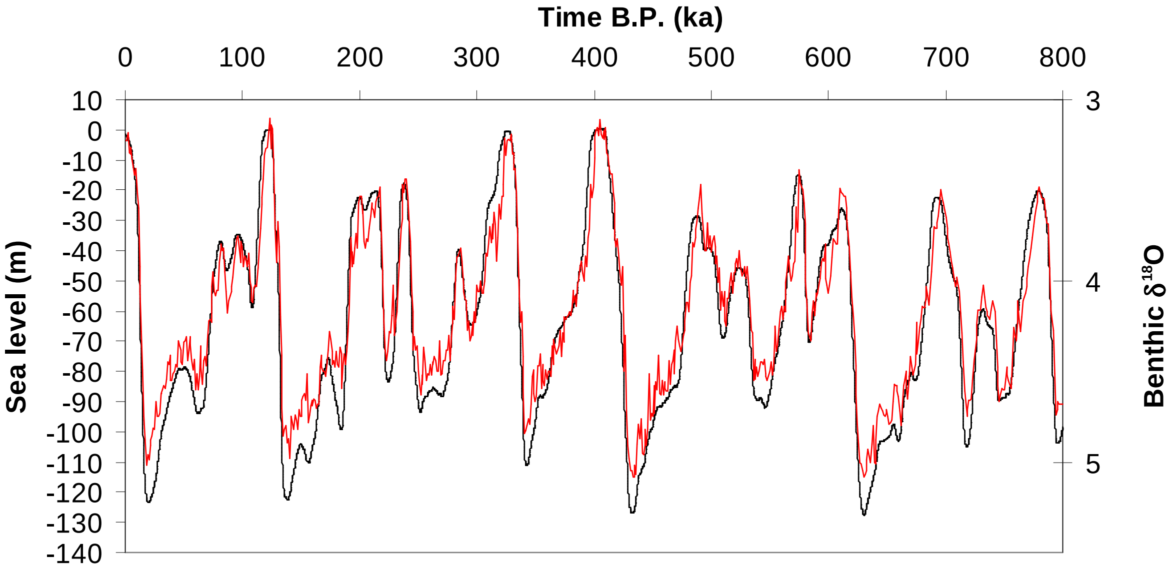

Figure 9. Benthic $\delta^{18}O$ curve in red (after Lisiecki & Raymo, 2005) and sea level curve in black (Bintanja et al., 2005). Axis for $d^{18}O$ curve is inverted to facilitate comparison with sea level curve.

In order to used the data, the Lisiecki & Raymo (2005) oxygen isotope curve was first normalised in the following way:

1. The average $d^{18}O$ was calculated and subtracted from the original $d^{18}O$ values;
2. A curve plotting time on the X-axis and the (original $d^{18}O$ values – the average value) on the Y-axis was constructed;
3. This curve was used to find the most extreme $d^{18}O$ value and all (original $d^{18}O$ values – the average value) were divided by this value.
4. Now all values are normalised and lie more or less between -1 and +1.

Two more manipulations are needed before the curve is ready for use. Tebbens et al. (2000) could use the GRIP-curve directly because in ice high $d^{18}O$ values occur during warm and humid periods and low $d^{18}O$ values during cold and dry periods. The opposite is the case for marine oxygen isotope cores where low $d^{18}O$ values dominate warm periods and high $d^{18}O$ values cold periods. This means that the marine record mirrors the trend of discharge rates: low $d^{18}O$ values correspond to high discharges and visa versa. But we want a linear transformation whereby high $d^{18}O$ values correspond to high discharges. Therefore the normalised marine oxygen isotope curve was multiplied by -1. Now high $d^{18}O$ values correspond to high discharge values.

The second manipulation concerns scaling and linking of present day discharge rates to the oxygen isotope record in order to obtain discharges that fluctuate through time. An extensive overview of this procedure can be found in Tebbens et al. (2000) and Stemerdink (2007). The equation obtained through this procedure is programmed into Fluver 2 and linked to a file with the Lisiecki and Raymo (2005) normalised $d^{18}O$ values that were multiplied by -1. For every time step and every spot along the longitudinal profile the corresponding discharge will now automatically be calculated.
The equation obtained through the scaling process is:

Qw[i] = (qw [i] / 2.73) * (dd_sin+1.85)

Whereby -Qw [i] = Palaeodischarge at step i (place along the longitudinal profile) in m^3/s
-qw [i] = present day discharge at step i in m^3/s;
-2.73 = Sum of the amplitude of the normalised * -1 curve and the present day discharge value obtained through the normalised * -1 curve (dimensionless)

-dd_sin = normalised value *-1 of the oxygen isotope curve per timestep
-1.85 = amplitude of the normalised * -1 curve (dimensionless).

The aforementioned procedure describes the successful attempt to reconstruct palaeodischarge input for Fluver 2. However, another, yet failed, approach was devised to calculate palaeodischarge using pollen-derived precipitation estimates. Such pollen have been taken from deep sea sediments off the Galician continental shelf in front of the Miño outlet. The pollen record forms an almost continuous 430 ka long vegetation and climate archive for the Miño-Sil and to a lesser extent Douro catchments (Desprat, 2005). Precipitation estimates upon these pollen have been made for the warmer intervals (Holocene not included) and entail the periods 70-130 ka, 181-252 ka, 266-338 ka and 362-428 ka ago (Desprat, 2005; Desprat, pers. comm; Sanchez-Goñi, 2006; Sanchez-Goñi, pers. comm). Figure 10 shows these estimations.

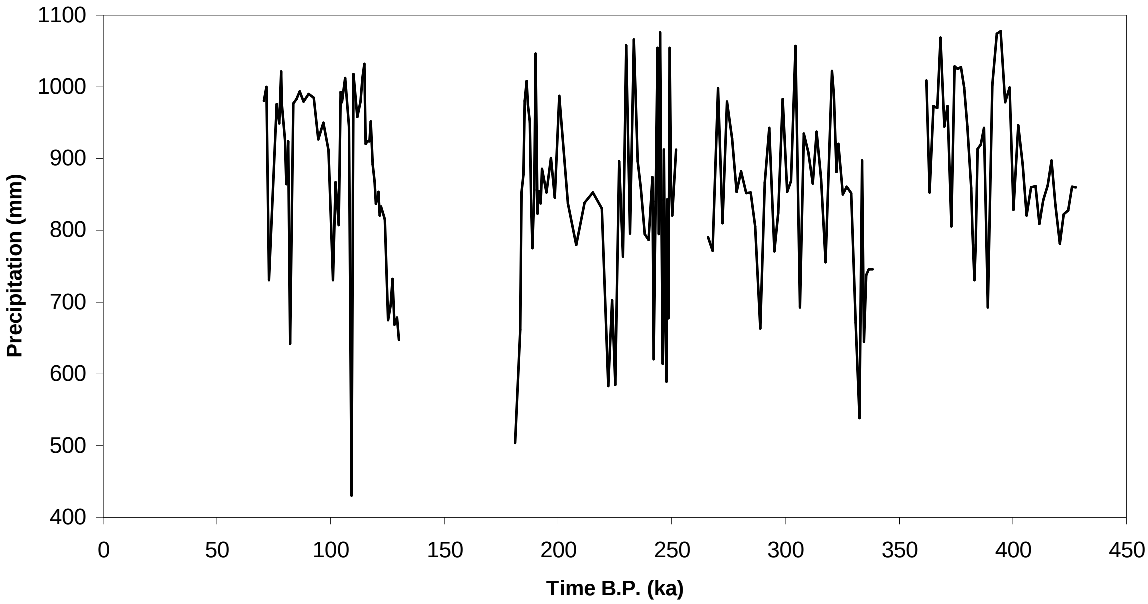

Figure 10. Estimated palaeoprecipitation for the Miño-Sil catchment (after Desprat 2005 and Sanchez-Goñi, 2006).

It is clear that all interglacials experience the same, wet climate with maximal precipitation rates of around 1050-1100 mm and that in general climate becomes much drier towards the glacial periods. The figure shows that for full glacial periods precipitation rates could not be reconstructed, most likely due to a scarcity of vegetation and hence, pollen.
As this pattern of high values for interglacials and low values for glacials also occurs in the marine oxygen isotope core, it is perhaps possible to find the same trends between changes in the precipitation curve and changes in the marine oxygen isotope curve. If such a trend exists both in timing and magnitude, then the missing precipitation values for the full glacial conditions can be reconstructed by using these trends to interpolate the missing data. After all, regions downwind of polar fronts are most susceptible to changes (e.g. displacements) of these polar fronts and connected precipitation patterns. Vegetation patterns in NW Iberia are therefore expected to show the largest reaction to changes in moisture availability and temperature changes (Boessenkool et al., 2001).
Unfortunately, a comparison between the two curves (Figure 11) shows that the already mentioned trend is visible in both, but that the timing of variation in precipitation is not in agreement with changes in $d^{18}O$ values. For instance, precipitation values during the period 362-428 ka show a tendency towards high values even though the marine oxygen isotope curve already registers almost full glacial conditions. Another example is the transition from glacial to interglacial conditions around 130 ka. Interglacial conditions are registered in both

curves, but the climatic optimum is registered ~10 ka earlier in the benthic core. This means that the marine data cannot be used to interpolate the precipitation data and rightfully questions the validity of using a marine oxygen isotope core to simulate palaeodischarge dynamics. Such a proxy may be applicable to broadly simulate discharge rates over glacial-interglacial timescales, but is certainly not applicable to smaller timescales.

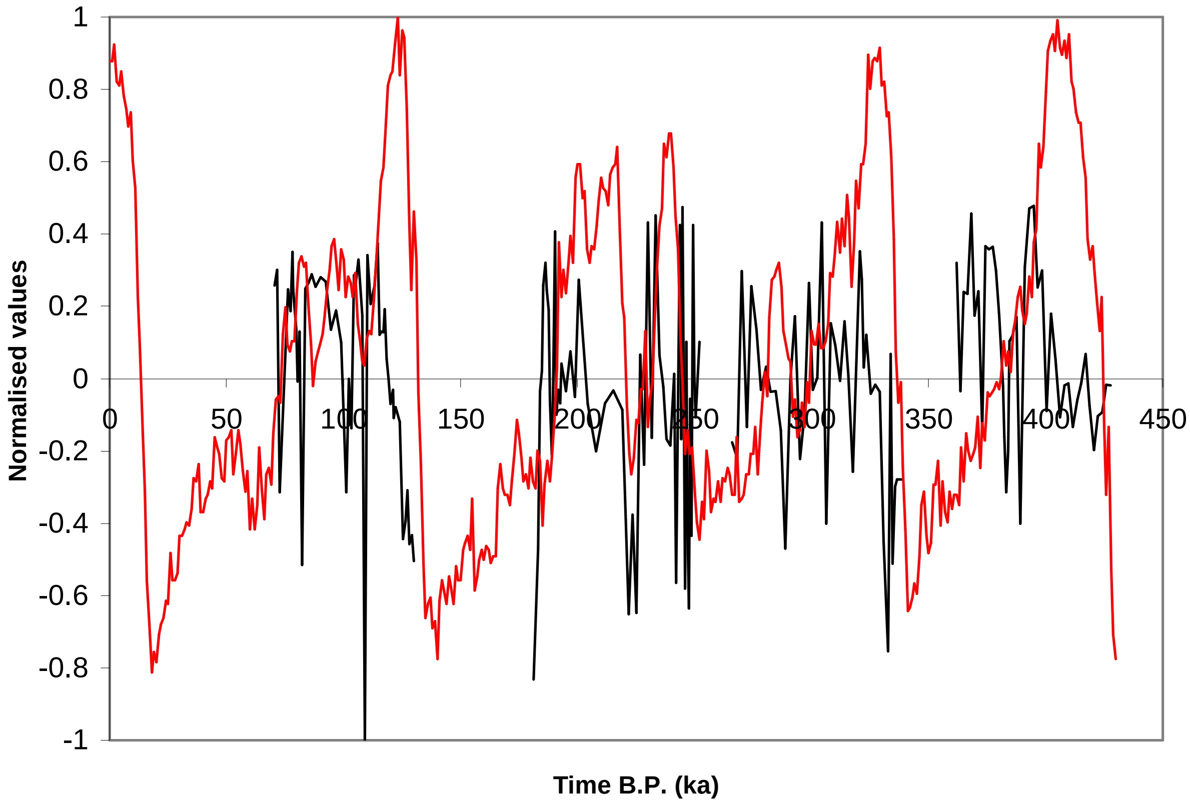

Figure 11. Normalised precipitation data in black (Desprat, 2005; Sanchez-Goñi, 2006) and normalised d^{18}O values in red (Lisiecki & Raymo, 2005). d^{18}O values are multiplied by -1.

7.4.2 Catchment simulation: from 3D to 2D

The first part of Chapter 7.4 dealt with how discharge through time can be reconstructed using a proxy. It was not discussed however how discharge is calculated in space. As Fluver 2 is a 2-dimensional model, it does not use a 3-D structure such as a DEM to make space-related discharge calculations.
Instead, discharge is calculated along the Miño-Sil longitudinal profile in a 340 m step-wise increasing way. Each step can be considered as a segment, just as a cell in a DEM is one segment and each step from the source of the Sil downstream to the Atlantic Ocean experiences a slight increase in discharge.
Contemporary discharge data was obtained from Rio-Barja & Rodriguez-Lestegas (1992) who calculated discharge for the entire Galician Miño-Sil basin, including all major subcatchments. Their discharge estimations of the Miño-Sil main trunk channel are based on a combination of independent weir data and a summation of evapotranspiration/catchment area calculations for the sub-catchments.
Fluver 2 cannot handle a sudden large increase in discharge in just one step, so to prevent model instability discharges from a sub-catchment into the main channel were spread out over a certain number of 340 m steps instead of added in just one step. This method looks very much like the one of Tebbens et al. (2000) using the catchment factor but I would like to stress that this is a different method and that I did not use this catchment factor in my calculations. Allow me to elaborate a bit more on this. Let us consider a transect of 10 steps long. Each step is 340 m so the total length of the transect is 3.4 km. The beginning of the

transect is A and the end is B. Weir data is available for A and B. At point A river discharge is 10 m^3 and at point B 20 m^3. In between A and B the streams of two sub-catchments enter our 10 step long transect and each stream adds 5 m^3. It is of course logical that the attribution of the two sub-catchments of 2*5 = 10 m^3 accounts for the increase of 10 m^3 at A to 20 m^3 at B.
A sudden increase with 5 m^3 in one step renders the model unstable, so we have to find an alternative. What I did is spreading the total additional 10 m^3 discharge equally over the 10 step length of the transect. So at step 1 discharge becomes 10 [weir data at point A] + (2*5)/10 [total number of steps] = 11 m^3. At step 2, the discharge becomes 10 + (2*5)/10 + (2*5)/10 = 12 m^3. At step 10 (the place where B is), total discharge is 10 + ((2*5)/10) *10 steps =20 m^3. This is exactly the same discharge as the weir registered at point B. In this way the increase in discharge for the entire Miño-Sil was calculated, using 7 weir data points as control points. The only exception being the Miño-Sil confluence, where discharge was added at once. Down stream of the confluence, the most complete set of fluvial terraces was found. Spreading the discharge over this area might have implications for modelled terrace formation. As the model did not become instable, discharge was added in one step. Figure 12 shows the contemporary discharge.
For the Leonese part of the Sil no discharge data was available. I contacted the hydrographic offices in Galicia, Leon and Asturias countless times, but every time I was redirected to another person. After a dozen phonecalls, emails and even a personal visit to the A Coruña office, I gave up. Instead, I calculated discharge for this stretch by dividing the discharge given at the first weir point on the Galicia/Leonese border by the total number of steps in between the source of the Leonese Sil (step 1) and this Galician weir point.

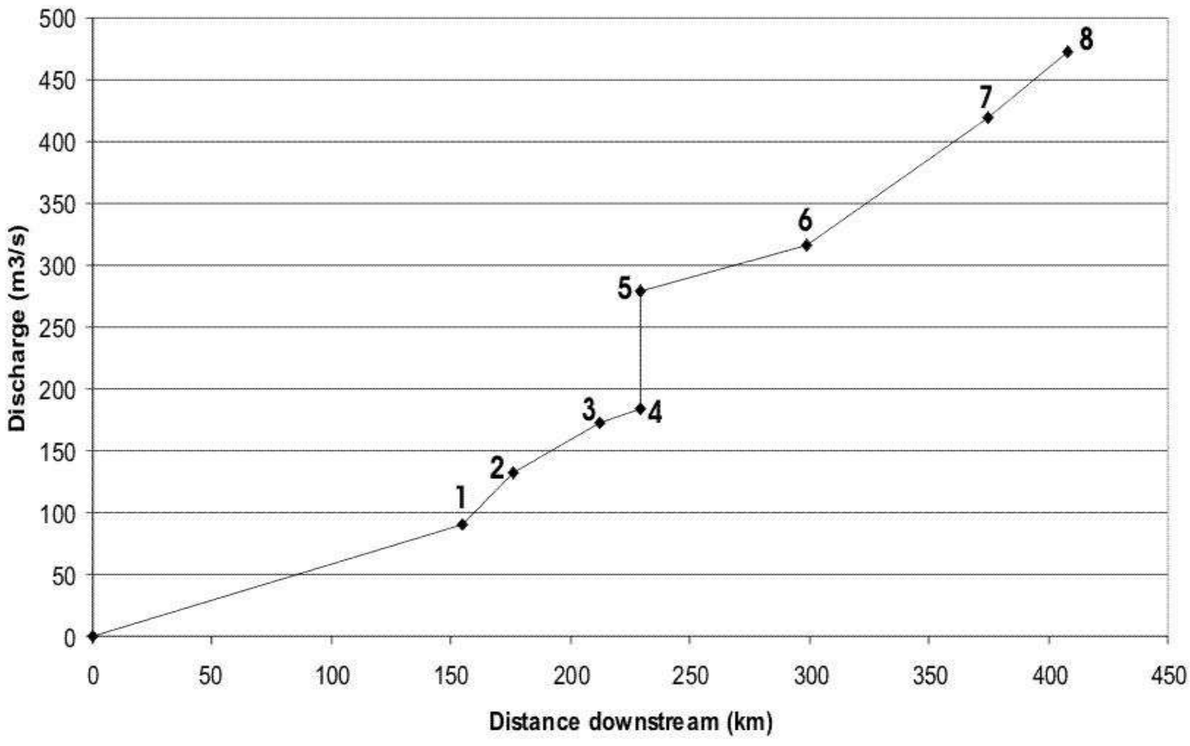

Figure 12. Contemporary discharge of the Miño-Sil system. Numbers 1 to 7 refer to weir data points: 1. San Martiño, 2. Segueiros, 3. San Estevo, 4. San Pedro, 5. Miño-Sil confluence at Os Peares, 6. Frieira, 7. Current land-sea transition. Number 8. shelf break. This is not a weir data point, but to get an overview of the discharge for the entire profile, number 8 was added.

7.4.3 Hillslope sediment supply

Fluver 2 can cope with non-fluvial sediment supply derived from hill slopes, for instance in the form of overland flow or landslides. This hill slope sediment supply has been found to be very important in for instance the mountain reaches of the Meuse catchment (Tebbens et al., 2000) where during glacial periods superficial run-off due to permafrost and the absence of a vegetation cover governed landscape development. The vegetation record of the past 430 ka in NW Iberia shows a different picture altogether. During the past 5 interglacials and interglacial/glacial transitions, vegetation has always been present with pine forests during the colder periods and oak forests during the warmest periods (Desprat, 2005). Even during the full glacial conditions of the past 65 ka vegetation patterns switched from grassland during stadials to open woodland during interstadials (Roucoux et al., 2001; 2005). It was even suggested that during the last glacial NW Iberia acted as a refugium zone for deciduous trees (Naughton et al., 2007).

On the other hand, Garcia-De Celis (1997) argues that during glacials slope derived sediment supply did play an important role in the Leonese mountains where the headwaters of the Sil are situated. Indeed, a look on the 1:50.000 geological maps of the area shows that many cold-climate associated landslides and alluvial fans are found at the foot slopes of these mountains.
All in all, hill slope sediment supply was probably only a factor of importance in the mountainous hinterland of the Miño-Sil system and played a minor or no role in the downstream region. After all, the lower valley sides and mountain slopes were always under vegetation. The alluvial terraces in the Atlantic reach of the Miño are probably not influenced at all by hillslope derived sediments far upstream. For this reason, the hill slope sediment supply parameter was not used in the modelling exercise.

7.5 Sea level

Long-term regional records on past sea levels are not available either. Therefore the reconstructed 1 Ma global sea level record of Bintanja et al. (2005) is used. See Figure 9. They coupled changes in sea surface temperatures to Northern Hemisphere ice sheet growth and linked these to the globally applicable stack of deep sea records of Lisiecki & Raymo (2005). Their results were validated using the existing coral reef records of the Red Sea (Siddall et al., 2003) and of New Guinea and Barbedos (Lambeck & Chappell, 2001). The modelled record of Bintanja et al. (2005) has the advantage that it uses the marine stack of Lisiecki & Raymo (2005). This same stack is used for the palaeodischarge simulation in this thesis and thus ensures a certain level of coherence between changes in sea level and climate/precipitation. Also, they have a common time-scale which prevents artificial time-lag problems between the onset of sea level and climate fluctuations. Lastly, the data of Bintanja et al. has a practical advantage as well: data is available in spread sheet format with sea level estimations on a 0.1 ka time interval, making this the most detailed and user friendly sea level record available.
A final note concerns the natural time-lag between sea level and climate changes. Fluver 2 is run with sea level lagging 1 ka behind precipitation changes as proposed by Veldkamp & Van Dijke (2000).

7.6 Lithological control

The inherent resistance of bedrock to erosion plays an important role in the capacity of a river to incise and transport material. The harder the underlying bedrock is, the more time a river needs to strip off sufficient sediments to carry and deposit further downstream. It is logical to assume that a river more easily forms fluvial terraces in a sedimentary basin than in an environment of granite bedrock. Proença-Cunha et al., (2005) for instance found that within the Spanish/Portuguese Tagus river basin alluvial terraces only formed in the softer material, whereas incision took place in the harder bedrock. For this reason an extra bedrock erosion resistance factor is added to Fluver 2. A first step in determining this factor is classifying the lithology of the Miño-Sil catchment. On basis of 1:50.000 geological maps the study area was divided into four distinct lithological regions:

1. The Leonese/Galician Cantabrian range consists of Palaeozoic metamorphic sedimentary rocks, mainly of slates, schists, quartzites and sandstones.
2. This Cantabrian range is interspersed with small Tertiary sedimentary basins consisting of conglomerates, gravels, sands, muds and clays.
3. The greater part of Galicia and Northern Portugal up to the city of Tui is made up of Precambrian granites and plutonic granodiorites with occasional Precambrian schists and quartzites.
4. Tui-Atlantic Ocean: In this area crustal extension took place and possibly formed the Rias Baixas. Precambrian to Lower Paleozoic para-gneisses, slates, schists and different kind or granites are found in N-S running bands.

Existing literature was used to determine erosion resistance rates. NW Iberia is an old cratonic surface and therefore literature treating similar landscapes is used, ensuring representative rock strenght values. Clayton & Shamoon (1998) investigated entire Great Britain using regional relief as an indication for weathering resistance. They found a positive correlation between rock age and erosion resistance. Within a group of rocks of similar age, quartzites and sandstones tend to be the most resistant, followed by granite and gneiss. Metamorphic sedimentary rocks (slates and shales) are less resistant. The most resistant rocks they encountered were Precambrian quartzites and sandstones (Clayton & Shamoon, 1998). It happens that the Lower Miño river terraces are entirely made up of quartz(ite) and sandstone conglomerates, thus confirming the observation of Clayton & Shamoon.
For the east Tennessee Appalachians, Mills (2003) related local relief, regional relief and slope to bedrock resistance. He classified around 50 rock types, groups and formations on a 0 to 100 scale. The also found that coarse-grained sandstones had the highest resistance (values ranging from 89 to 71), followed by metaplutonic gneiss and granite (values around 50). Shales had the lowest resistance values (25 to 9). Using this information, I classified the four lithological zones as follows:

1. The Galician/Portuguese Precambrian granite and granodiorite zone has the highest bedrock erosion resistance factor, namely factor 3.
2. The Tui-Atlantic Ocean area is very similar to the granite/granodiorite zone, but the presence of a more diverse lithology and the foregoing crustal extension makes that the crust could be a little more brittle and therefore less resistant. A factor 2.5 is assigned to this zone.
3. The Cantabrian metamorphic zone consists of a mixture of slates, schists, sandstones and quartzites, but the vast majority is slate and schist. The sandstones and quartzites are therefore neglected. Mills (2003) estimated values for shale around 25 to 9. 5 is taken as a mean value and it is assumed that Mills' shale is representative for the slates and schists in the study area. After all, shale is the same kind of rock as slate and schist, but in just a slightly different state of metamorphosis. In this way we see that the value 15 is about a third of the value for Mills' granite/gneiss (around 50). This means that the factor 1 is assigned to this zone.
4. The sedimentary basins receive a value of 0.1

These values are incorporated in the model by dividing the erodability factor (k-factor) by these values for the different sectors along the longitudinal profile.

Chapter 8 Calibration

Fluver 2 was calibrated by means of 3 parameters. The first parameter, the so-called *k-factor* (*k-sed*), fine-tunes the erodibility of the river bed, providing a measure of control of the amount of sediment that was detached from the river bed. The second parameter was used to set the transport distance of sediment before its actual deposition. The third parameter, which was not used in the present study, can be used to regulate hill slope sediment supply.

The model is tested with a combination of the erodibility (*k-sed*) and travel distance (*Dis*) parameters. The outcome of a simulation using different combinations of *k-sed* and *Dis* can be depicted with *k-sed* on the X-axis and *Dis* on the Y-axis. A certain field on the plot shows a good combination of parameters, another field shows less realistic combinations, and there are fields where combinations are not realistic. The extremes of the plot combine a set of parameters that render the model unstable. The plot is drawn on the basis of criteria 1 and 2 (see below). This leaves a number of possible combinations of *k-sed* and *Dis* which are narrowed down by applying the remaining criteria 3 to 6. In the end, the simulation that has a best total score for all criteria is the most plausible one. For each scenario a new calibration plot was created.

A suitable model run has to fulfil a number of criteria. These criteria are based on the following rules and assumptions:

1. During the simulated 800 ka, the Miño-Sil is supposed to be in a state of semi-equilibrium. River incision keeps pace with tectonic uplift. This means that after a run of 800 ka, the simulated profile must be similar in altitude to the current profile.
2. Because the system is in a state of semi-equilibrium, the shape of the simulated profile will have to be the same as the shape of the current profile. The profile is only calibrated in shape and height for the currently emerged part of the river. In the now submerged area in all model runs a delta is formed. Because the model does not incorporate a set of equations that simulate sediment removal by ocean currents, in all cases an unrealistic delta is generated.
3. At 2 places along the longitudinal profile, total simulated deposition is reflected against field evidence. At step 985 (Salvaterra) and step 1053 (Furna/Goian), the highest number of enclosures was found for various terrace levels (see Appendix 6, Plates 4 and 16-19). On the basis of these enclosures, an estimation was made for the amount of alluvial material present. A terrace may have a scarp face of 10 meters, but that does not mean there is 10 m of sediment present. In the lower Miño terrace incision occurred in the underlying weathering mantle as well (Alves, 2004). At Salvaterra, enclosures for 4 terrace levels were found. For each terrace, the proportions of fluvial sediment and saprolite were estimated. Then the mean fraction fluvial sediment was calculated for these 4 terraces. In total, 42 percent of a given Salvaterra terrace consisted of fluvial material. Assuming that all 8 terrace levels have a similar sediment distribution, then the total incision for T1-T7 (~75 m) can be estimated. This yielded 32 m (42% of 75 m) of fluvial sediment for Salvaterra. 4 enclosures were found at Furna/Goian as well. The proportion of fluvial material was 68% at this site, which translates to 51 meters of fluvial sediment. The larger amount of sediment at the Furna and Goian villages can be explained by the relative proximity to the Atlantic Ocean (Salvaterra is located 23 km further upstream). As we will see later on, fluvial sediment is laid down in the form of a backfilling sedimentary wedge near the coast. The closer to the coast, the thicker the stack of sediment will be. This implies that upstream of Salvaterra, the sedimentary wedge will thin out even more until no sediment remains. These estimations should be considered as *minimum* amounts of sediment, as erosion was not accounted for. Also, the applied model is a 2-D model, which implies that the sediment that was deposited not directly along the longitudinal profile but higher up the river bed is not simulated.

4. The model should be able to simulate alternating erosion and depositional phases in the areas that harbour fluvial terraces. After all, an alternation of erosion and deposition might indicate terrace formation. See Table 6.
5. Because the fieldwork was carried out in the lower Miño section, the more reliable terraces count may be expected. A reliable run should therefore simulate 8 or 9 (depending on the scenario) phases of alternating erosion and deposition phases close to the coast. These should match the terraces found in the field.
6. The simulated terrace height should mimic the terrace heights obtained from field observations. The simulated altitudes should be considered maximum heights, because real terrace height cannot be reconstructed as a consequence of post-depositional erosion.

Table 6. Locations along current river profile where alluvial terraces are found.

Location	Start km	End km
East of Vilablino	16	23
Paramo do Sil	46	52
Toreno/Noceda basin	62	70.5
Bierzo & O Barco & Valdeorras basins	85	157
Basin of Quiroga	175	182
Ribadavia	275	288
Lower Miño	300	375

Chapter 9 Results

9.1 Calibration

9.1.1 Calibration plot –criteria 1 and 2

Figure 13 shows the calibration plot with *k-sed* on the abscissa and *Dis* on the ordination axis. The plot shows a field where the simulated profile is situated *below* the current profile (marked "-"). This is caused by a combination in which either a high *Dis* or a high *k-sed* value prevails. A combination of high *Dis*/low *k-sed* means that there is little erosion and high sediment mobility, causing sediment transport out of the system. This in turn would produce a significant lowering of the simulated profile. A combination of high *k-sed*/low *Dis* means that there is severe incision which is not compensated for by the amount of transported sediment. This also causes a too strong lowering of the simulated profile. Alternatively, a relatively high value of both *k-sed* and *Dis* values means that erosion and sediment transport are not in equilibrium yet.

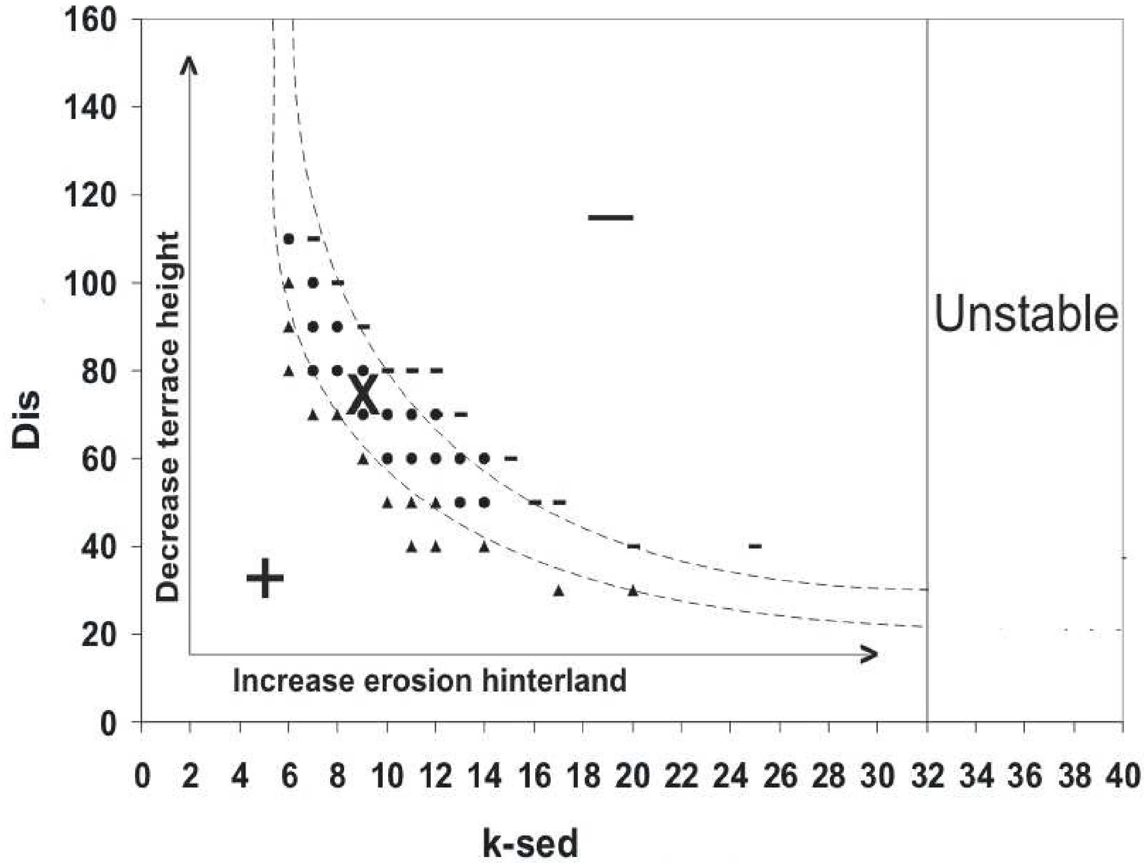

Figure 13. Calibration plot for scenario 1b with the erodability factor *k-sed* (*10^{-11} m^{-2}) on the X-axis and sediment travel distance *Dis* (km) on the Y-axis. "+" indicates too much deposition or too little erosion for simulated profile and "-" indicates too much incision. "X" is the field where plausible model outcomes are found. Dashed line indicates borders between +, -, and X-fields. "Unstable" means that in this field the model became unstable. Triangles indicate model runs generating too much depostion/too little erosion, dots are model runs within the X-field, and minuses are model runs in the erosion field. "Decrease terrace height" and "increase erosion hinterland" are discussed in Section 9.1.2.

The field showing the plus “+” sign represents the combination of parameters that generates a simulated profile situated *above* the current profile. This is caused by a combination of high *Dis*/low *k-sed*, low *Dis*/high *k-sed* or a combination of relatively low *Dis*/*k-sed*. All these combinations lead to either too little erosion (incision) or overcompensation by sediment transport. Overcompensation by sediment transport in both the “-“ and “+” fields originates from the upstream part of the profile (Leonese mountains, see Figure 8). For almost all model runs this region is severely eroded and very difficult to bring in equilibrium with the contemporary profile. The original assumption that the Leonese hinterland experienced the same uplift rate as Galicia may have to be revised as in all model runs the mountain range eroded hundreds of meters. After a number of trials the uplift rate was increased from ~0.01 m/ka to 0.03 m/ka. This brought the entire profile in a better equilibrium.
The field marked “x” shows realistic combinations of *k-sed* and *Dis*. In this domain the best model results will be found. We see that this domain follows a clear trend from the left upper corner of the plot to the right lower corner. The trend is of course a visual representation of what was written in the first paragraph above.
The plot shows that the model is sensitive to both *Dis* and *k-sed*. The model is more sensitive to changes in *Dis* than in *k-sed*, probably because the *Dis*-scale is given in units of 10 meters, whereas the *k-sed* scale is given in units of 1. If *Dis* were in units of 1, *k-sed* would be the more influential parameter.

9.1.2 Calibration terrace formation –criteria 4 to 6

Figure 16 displays 2 curves at steps 985 and 1053 along the longitudinal profile. The curves show an increase or decrease in river profile height (dH in the legend). These changes in profile height are caused by erosion and deposition. During certain time periods there is a sediment build-up (aggradation) and each period is terminated by a sharp erosion or incision phase. If these phases are combined with the total calculated uplift per time step, a reconstruction of the generated terrace height can be given. So the figure basically shows the aggradation and incision of fluvial terraces through time. In an ideal situation, the predicted terrace heights agree with the terrace heights found in the field. These curves are used to decide which simulation suits criteria 4 to 6 best.

Additional analyses were performed to elucidate whether a systematic change of either *k-sed* or *Dis* leads to a predictable pattern of change. The calibration plot and Figure 16 were combined to see if certain trends exist. These trends can be used to predict the effect of certain combinations of *Dis*/*k-sed* on terrace formation. The following trends were observed:

- If *Dis* is increased for a given *k-sed* (for instance an increase from *k-sed* 11 and *Dis* 50 to *k-sed* 11 and *Dis* 60 to *k-sed* 11 and *Dis* 70), simulated terrace height decreases. This applies to each *k-sed* value in the X-field.
- If we move horizontally across the field, that is, if we increase *k-sed*, the number of simulated terraces increases. For *k-sed* 7, 6 terraces are formed; for *k-sed* 8 and *k-sed* 9, 7 terraces are formed. From *k-sed* 10 onwards, 8 or 9 terraces are formed.
- The curve at step 985 and step 1053 in general show the same amount of terraces, but with a difference in height. Simulated terraces at step 985 are situated 20 to 30 m higher, whereas in reality the difference is negligible.
- This difference of 20 to 30 m remains constant for each combination of *k-sed*/*Dis*.
- The erosion/incision phases in between deposition phases at step 1053 are more pronounced than for step 985.
- These incision phases become more pronounced with increasing *k-sed* values.
- If we increase *k-sed*, the lower terraces decrease in height, whereas the 3 highest terraces remain on the same height.
- The more we move to the right on the horizontal axis, the more the upstream part of the profile is eroded. From *k-sed* 13 to 14 onwards, the hinterland erodes too much.

- Looking diagonally for such trends in the calibration plot does not help much because certain horizontal/vertical trends conflict with each other when tested diagonally. For instance, an increase in *Dis* along the vertical axis causes a decrease in terrace height. An increase in *k-sed* along the horizontal axis has a similar effect. But a diagonal decrease in *Dis* and diagonal increase in *k-sed* annihilates both trends so that no linear trend remains.

These observations teach us that 8 terrace levels are found from *k-sed* 10 onwards. This considerably narrows down the number of plausible model runs. But if we increase *k-sed* too much, the hinterland is increasingly eroded. This places the left hand and right hand boundaries in the X-field at 10 and 13 to 14 *k-sed*. We also see that a too large increase in *k-sed* will trigger terrace formation below the altitude where they are found in the field, up to the point where formation occurs below present river level. Because there is a fixed height difference between the terraces at step 985 and 1053, it is not possible to have synchronous terrace formation at the same altitude.

The disparity in terrace heights at steps 1053 and 985 was found for all model runs. It is therefore suggested that the problem is not an artefact of the calibration procedure, or of differences in uplift input, but caused by something else. The currently submerged part of the profile could be too steep with a too sudden transition at 375 km. Sea level decline could cause an incision that is stronger nearby the sea, generating a significant gradient in terrace levels over time. That explains why terrace levels at the more coastward step 1053 are situated lower than at step 985. This idea seems confirmed by the speed at which the cliff face at 375 km (Figure 8) is eroded. Already in the first 30 ka of a random model run, the cliff face was incised up to the prevailing sea level. It would explain why terraces T6, T7 and T8 (Figure 5) are not found as close to the current coastline as the other terraces are. After the formation of T6, the Miño could have incised considerably, lengthened its profile and formed terraces T0-T5 between 35 and 52 km along the profile.
Consequently, the validity of simulated terrace heights at steps 985 and 1053 should be questioned. It is obvious that the terraces at step 985 are situated 20 to 30 m too high up in the landscape. In the field, the youngest terrace is found at 7.3 m a.s.l., but the simulated terrace starts between 20 and 30 m. The terraces at step 985 should therefore not be used as a means of terrace height calibration. Ironically, the simulated altitudes of the 3 highest terraces are in close agreement with field evidence. Most of the simulated terraces at step 1053 are found at altitudes that match with field observations, but vigilance should be maintained. It is very tempting to use these terraces as a proof of model correctness, but we should not forget that the coastward simulated river profile gradient is too steep. So the results remain unbalanced and an agreement between simulated and real terrace heights might be coincidental. Simulated terrace heights at step 1053 are therefore only used as a guideline.
Another point of caution is the high sediment peak at the beginning of a model run, around 786 ka. This peak is not considered a terrace, but either an artefact of model initialisation, or the result of an unrealistic initial profile, or of both. See the section on interpretation of modelling results for more information.

9.1.3 Erodability resistance factor

Model calibration using the erosion resistance factor turned out to be impossible. The original input (see Chapter 7.6) of 0.1 for the sedimentary basins, 1.0 for the Cantabrian metamorphic zone, 2.5 for the Galician Tui-Atlantic Ocean zone and 3.0 for the Galician granite area, caused a completely instable profile. The sedimentary basins were eroded hundreds of meters whereas in Galicia, incision could no longer keep pace with uplift. New model runs with random values of 0.5 for the basins, 2.0 for entire Galicia and 1.0 for the metamorphic range still caused an instable profile. Even setting the sedimentary basins at 0.8 and the rest of the profile at 1.0 caused too much erosion of the basins. In the end, the erosion resistance factor was discarded from the modelling exercise altogether. It is therefore

concluded that erosion factors found in the literature cannot be applied directly to the model. The model reacts too strongly to changes in the k-factor, so doubling or halving the k-factor for certain areas renders the profile unstable. For this reason a more subtle translation from “real world” erosion resistance values to model values is needed.
It can be argued that lithological differences play a minor role in the Miño-Sil system. After all, the current profile is most likely in a state of semi-equilibrium and strange jumps in the profile because of lithology are not visible. It is possible that the bedrock edges of the basins prevent a strong incision, because the river is “leaning” on and consequently eroding these edges instead of the basins. Perhaps lithology does play a role in the catchments of large lowland river systems such as the Rhine or Meuse. In these systems a clear distinction exists between the mountainous hinterland (Alps, Ardennes) and the large sedimentary basins of NW Europe.

9.2 Modelling results

For each scenario ca. 30 model runs were carried out. This number of runs was the minimum needed to establish the boundaries of the X-field in the calibration plot. There are 6 scenarios (0, 1a/b, 2, 3, 4) giving a total of approximately 180 model runs. For each scenario the best model run was chosen by applying the criteria of Chapter 10.1. These results are presented below.

9.2.1 Scenario 1a T0 set at the Holocene with differential uplift rates

33 model runs were performed. The best combination of parameters was a set with *k-sed* $11 * 10^{-11}$ and *Dis* 60 km. That resulted in a graded simulated profile of -5.56 m, meaning that the simulated profile was on average situated 5.6 m below the initial profile. There was slightly too much erosion in the upstream part of the profile, and also a bit too much deposition between 85 km and 160 km, but in general the simulated profile agreed quite well with the initial profile (Figure 14). The outcome therefore complies with criteria 1 and 2.

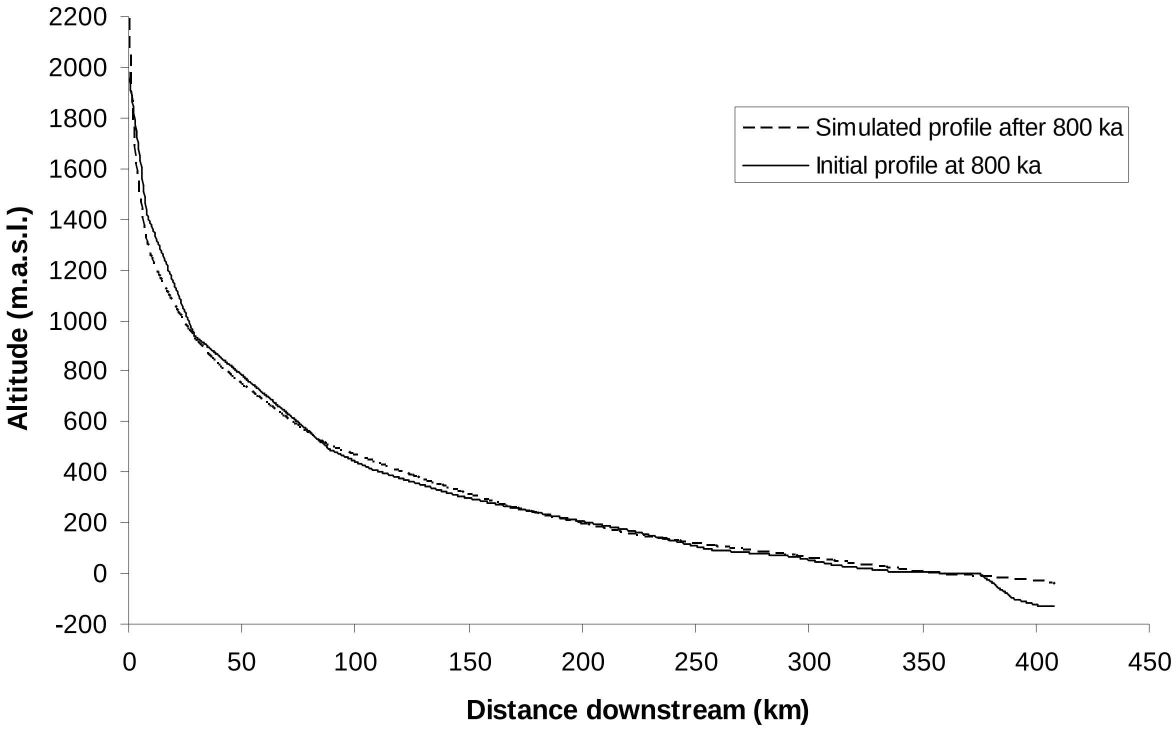

Figure 14. Initial profile at start model run and simulated profile after model run for scenario 1a.

Sediment yield at step 985 was 47.1 m and at step 1053 79.6 m. This agrees with the minimum values of 32 m and 51 m, respectively (criterion 3).
8 principal phases of erosion and deposition were recorded in the Profile Evolution Map (PEM, Figure 15) and the simulated terrace height curve (Figure 16). The PEM shows that these phases start at the coast and move upstream. The PEM registers more than de 8 main depositional phases, but these phases are not recorded in the simulated terrace height curve and are therefore unlikely to be found as separate terraces in the field. They are probably incorporated in the main sediment bodies, which are interpreted as fluvial terraces. The depositional events are found up to 272 km. This is in reasonable agreement with field evidence as the lower Miño sedimentary wedge is found up to the 300 km point along the profile. Perez-Alberti (1978) and Yepes-Temiño (2002) describe a terrace staircase at Ribadavia at 275-288 km along the profile (Table 5). These terrace heights agree very well with the downstream fluvial terraces and could be considered as an isolated extension. If this were true, the simulated terraces are found upstream at the same place as the terraces at Ribadavia.
The PEM shows that there is an almost continuous sedimentation going on in the Bierzo at ~100 km, which is interrupted by small erosion events in the second half of the PEM. The sedimentation phases at 272 and 400 km in the lower part of the PEM between 800 and 600 ka are probably the result of initialisation of the model run. The run immediately starts eroding and therefore an initial excess in sediment is generated. This excess is removed from the system during the model run. In a real world situation the system is already in a more steady state and this initial excess will not occur.
The other terrace sequences found in the smaller basins are not found on the PEM. The model was not capable of simulating them.
Reconstructed terrace heights at step 1053 are as follows: 10.5 m (field observation: 7.3 m), 15.8 m (13.4-18.9 m), 25.3 m (24.5 m), 33.3 m (31 m), 38.7 m (40.1 m), 45 m (52.9 m), 56 m (66.5 m) and 61.4 m (76.3 m). The first 5 terraces up to 38.7 m agree well with field evidence. The 45 m terrace is not found in the field and, based on chronology, linked to the 52.9 m terrace. If we would instead correlate on basis of height, then the simulated 56 m terrace could be linked to the real 52.9 m terrace. That would link the simulated 61.4 m terrace to the real 66.5 m terrace. Overall, that would improve height correlation but still leave us with one spare terrace at 45 m.

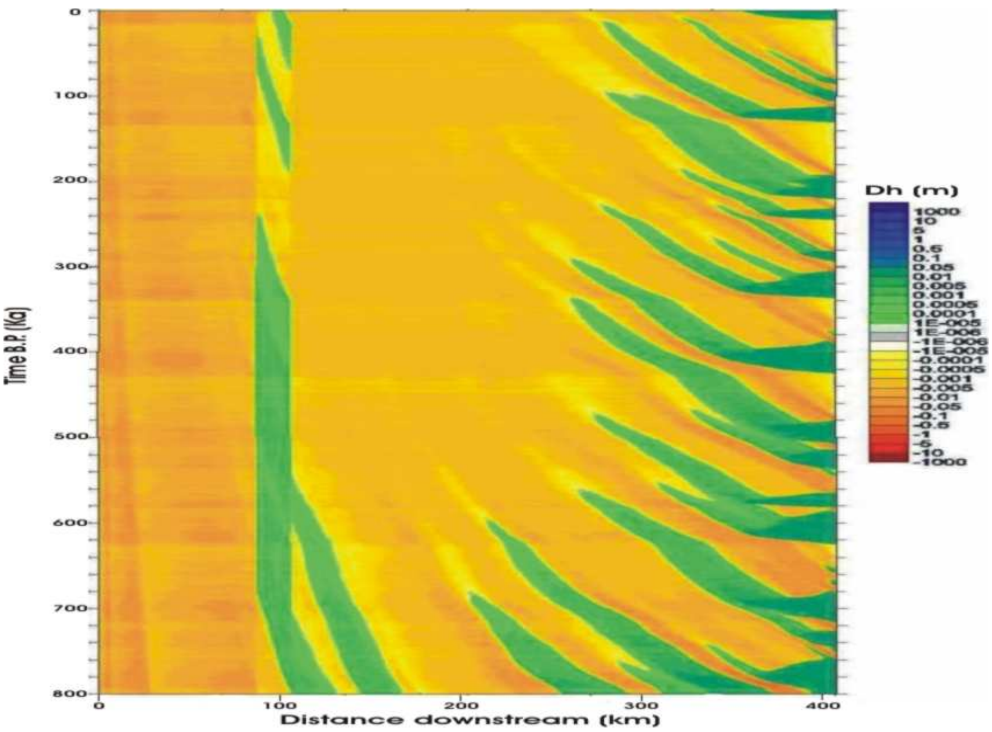

Figure 15. Profile Evolution map for Scenario 1a. Positive dH values indicate increase in height of the river bed and negative values a decrease. An increase is interpreted as deposition and a decrease as incision.

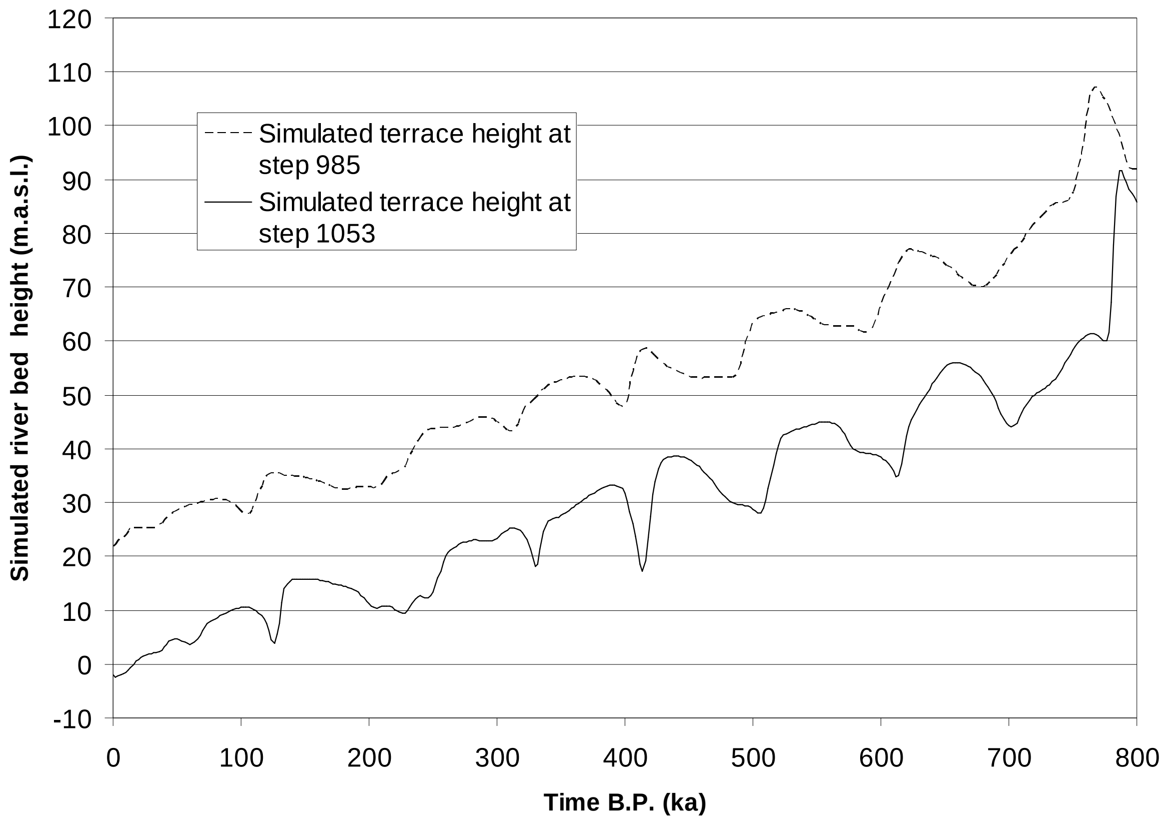

Figure 16. Reconstructed terrace heights for scenario 1a at steps 985 and 1053. A convex form indicates terrace aggradation and a concave form terrace incision.

9.2.2 Scenario 1b T0 set at Holocene with a mean uplift rate

Of the 30 runs, 6 model runs with a different combination of *k-sed* and *Dis* showed acceptable values for all criteria. Of these runs, the combination of *k-sed* 10 * 10^{-11} and *Dis* 70 km gave the best outcome. This yielded an end profile on average situated 7.7 m below the initial profile. The greater part of the incision can be attributed to the upstream part of the profile, whereas the simulated profile in the Bierzo and Galicia shows a strong coherence with the initial profile (Figure 17).

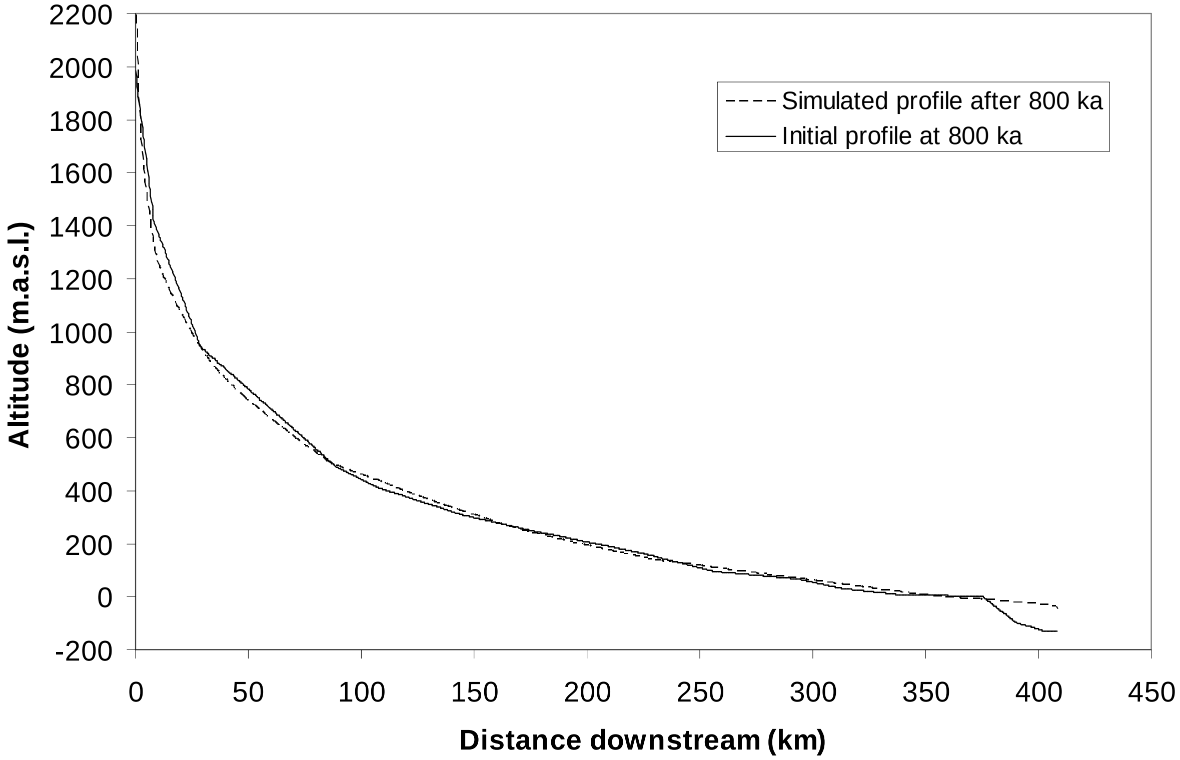

Figure 17. Initial profile at start model run and after model run for scenario 1b.

Total amount of sediment generated for step 985 was 41.4 m and for step 1053 66.3 m. This agrees with the minimum amounts of 32 m and 51 m as stated by criterion 3.
The Profile Evolution Map (Figure 18) and the simulated terrace reconstruction (Figure 19) show that there are 8 important erosion and sedimentation phases. The sedimentation phases start at the Atlantic Ocean and move upstream to the 272 km point. This is within reasonable limits as discussed in the results section of scenario 1a.
In the Bierzo region around 100 km there is a continuous sedimentation going on during the first 500 ka of the model run. The last 300 ka erosion dominates, interspersed by one or 2 depositional events only.
At 170 km, 272 km and 400 km, the same short depositional events as in scenario 1a are found. Once again, these are attributed to system initialisation and not to true processes.
The sedimentation phases at step 1053 agree to a certain extent with field evidence: 10.3 m (7.3 m), 16 m (13.4-18.9 m), 27 m (24.5 m), 33 m (31 m), 38.1 m (40.1 m), 43.6 m (52.9 m), 55.6 m (66.5 m) and 62.7 m (76.3 m). There is agreement for the lower 5 terraces, but we see that there is one simulated level too much around 40 m, and there are not enough simulated levels at altitudes above 55.6 m to agree with field evidence. Just as in scenario 1a, there is one terrace too much around 40 m (43.6 m in this case), that disturbs the terrace chronology.
This scenario shows that the correct amount of terraces is formed within reasonable limits for altitude as suggested by field evidence. This scenario is non-conclusive on the exact terrace height.

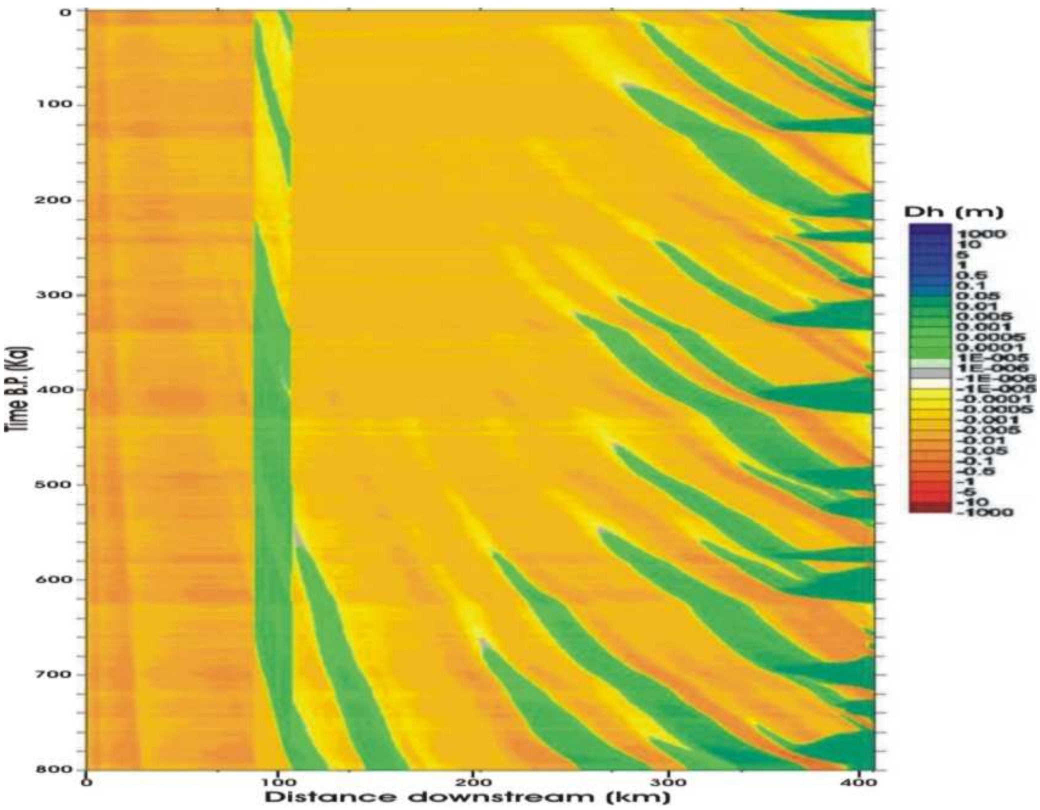

Figure 18. Profile Evolution Map for scenario 1b.

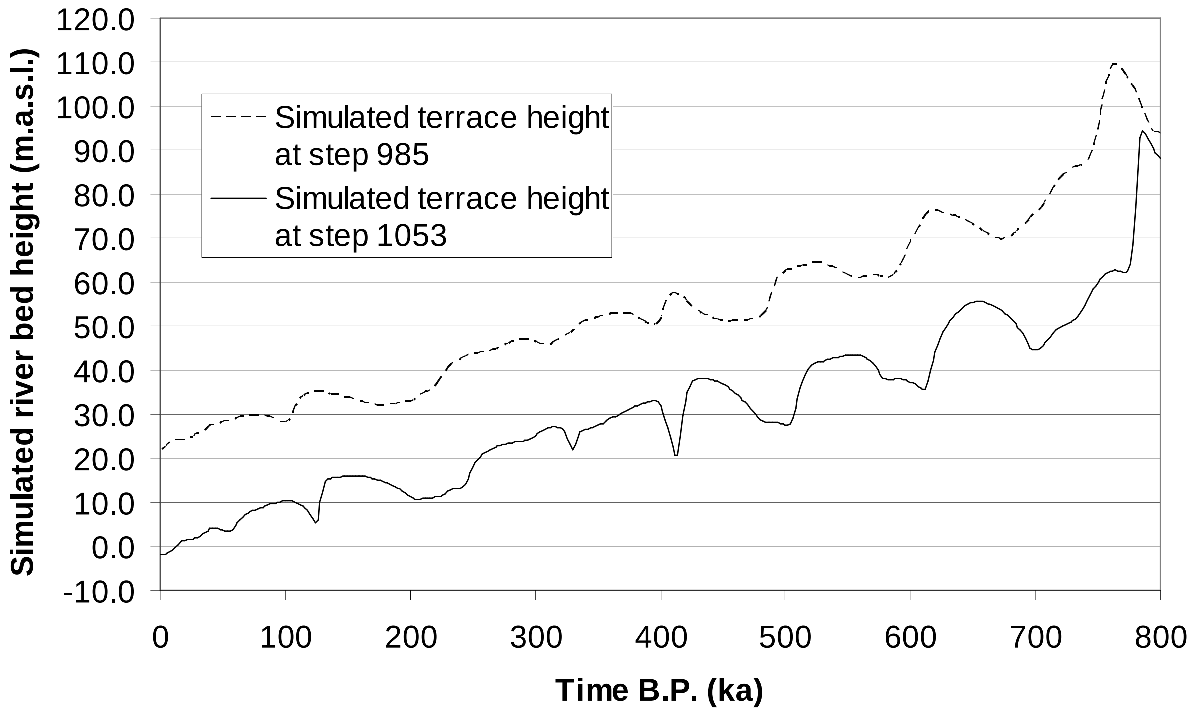

Figure 19. Reconstructed terrace heights for scenario 1b at steps 985 and 1053.

9.2.3 Scenario 2 T0 set at Eemian

23 model runs were performed and a combination of *k-sed* 10 * 10^{-11} and *Dis* 60 gave the best result. The simulated outcome is a concave, graded profile on average situated -1.7 m below the initial profile. The latter is approximated very closely with only a little too much erosion the first 25 km of the profile, and slightly too much deposition in the Bierzo area. See Figure 20. Generated sediment yield at step 985 and 1053 are 39.4 m and 66.5 m respectively. This complies with criterion 3.

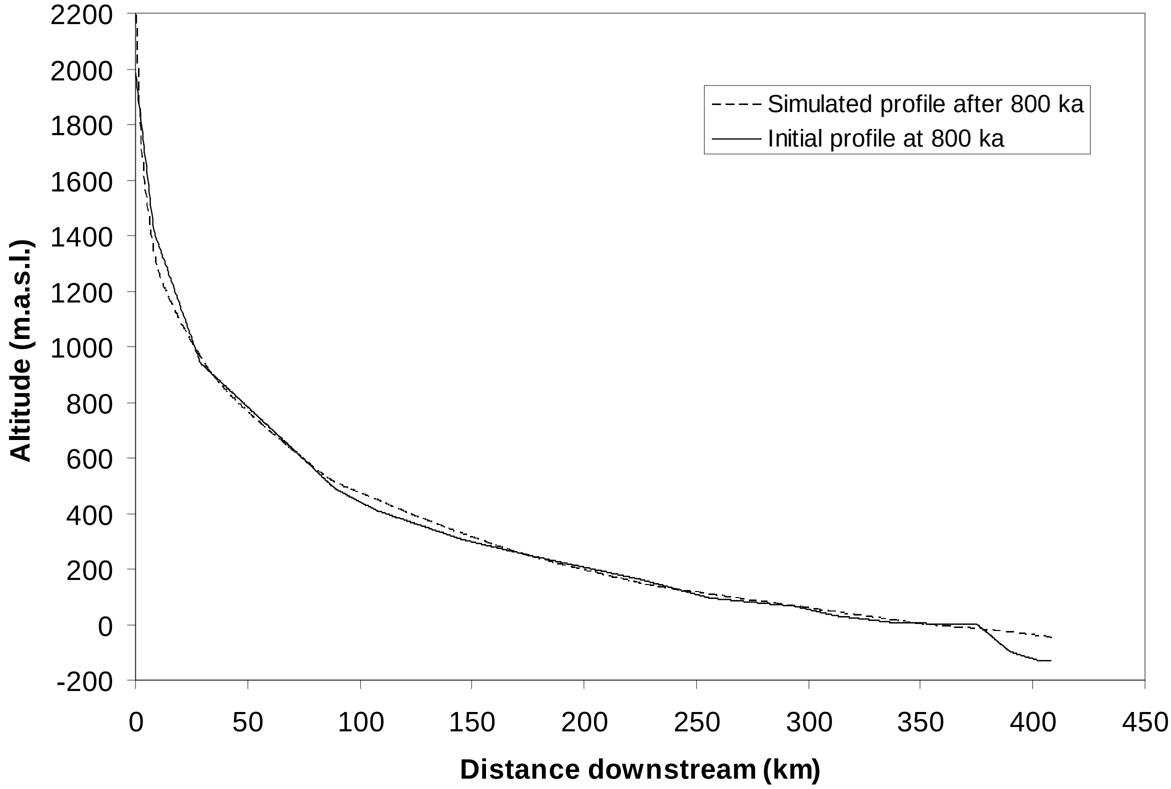

Figure 20. Initial and simulated longitudinal profile for scenario 2.

The PEM (Figure 21) and reconstructed terrace height curve (Figure 22) show that 8 main cycles of deposition and erosion dominate the record. The sedimentation phases start at the land-sea transition and move upstream towards 285 km. This is in agreement with field evidence (criteria 4 and 5). In the Bierzo sedimentation dominates the greater part of the simulation. Only the last 250 ka erosion takes over. At 170 km, 272 km and 400 km short depositional events are found during the initialisation period of the model run.

On the basis of the uplift curve (Figure 6), the formation of 8 terrace levels was expected. Thus the simulation yielded the expected amount of terraces. The modelled terraces were found at 5.1 m, 10.1 m, 18.6 m, 23.6 m, 26.4 m, 34.6 m, 47 m and 54.4 m. The majority of the simulated terraces are found below 30 m with only 3 terraces above this altitude, whereas in reality only 3 terraces are found below 30 m and the remaining ones are more evenly spread up to 76.3 m.
Overall, this scenario provides a satisfactory modelled profile and the number of terraces agrees with the scenario assumptions. The simulated terraces agree less than scenario 1a/b in height with field evidence.

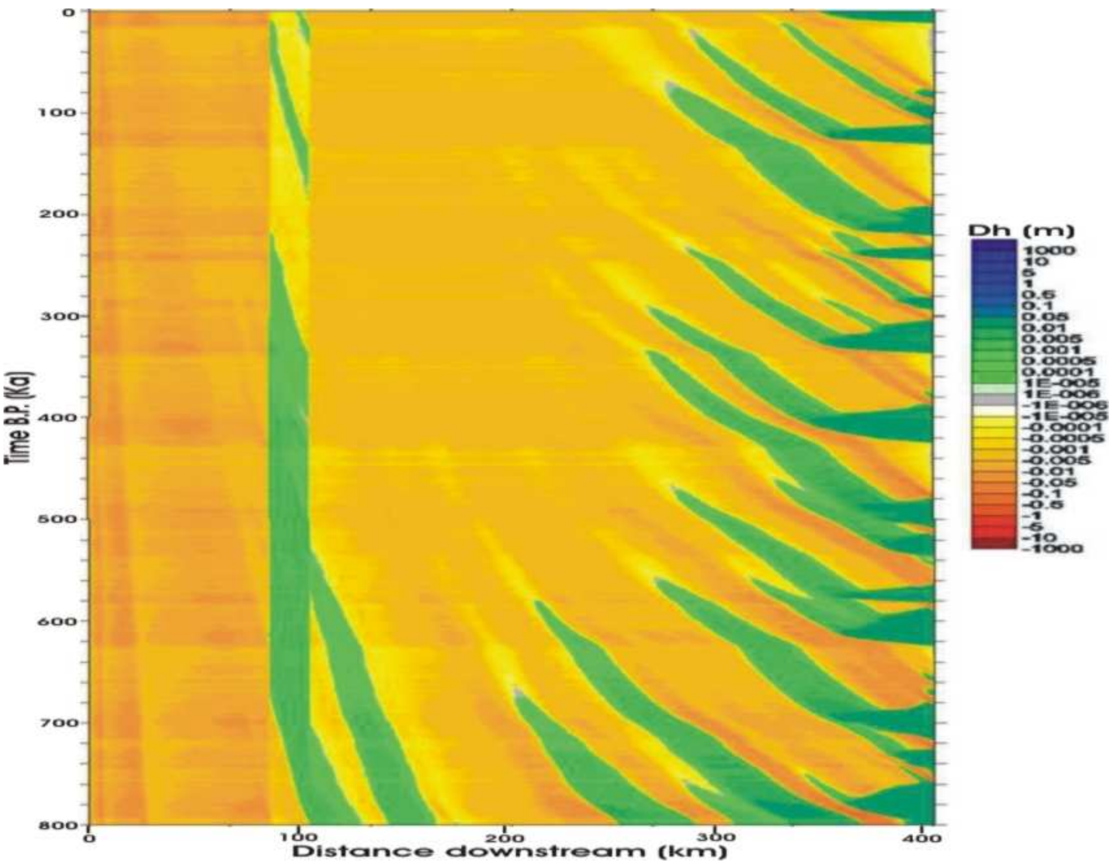

Figure 21. Profile Evolution Map for scenario 2.

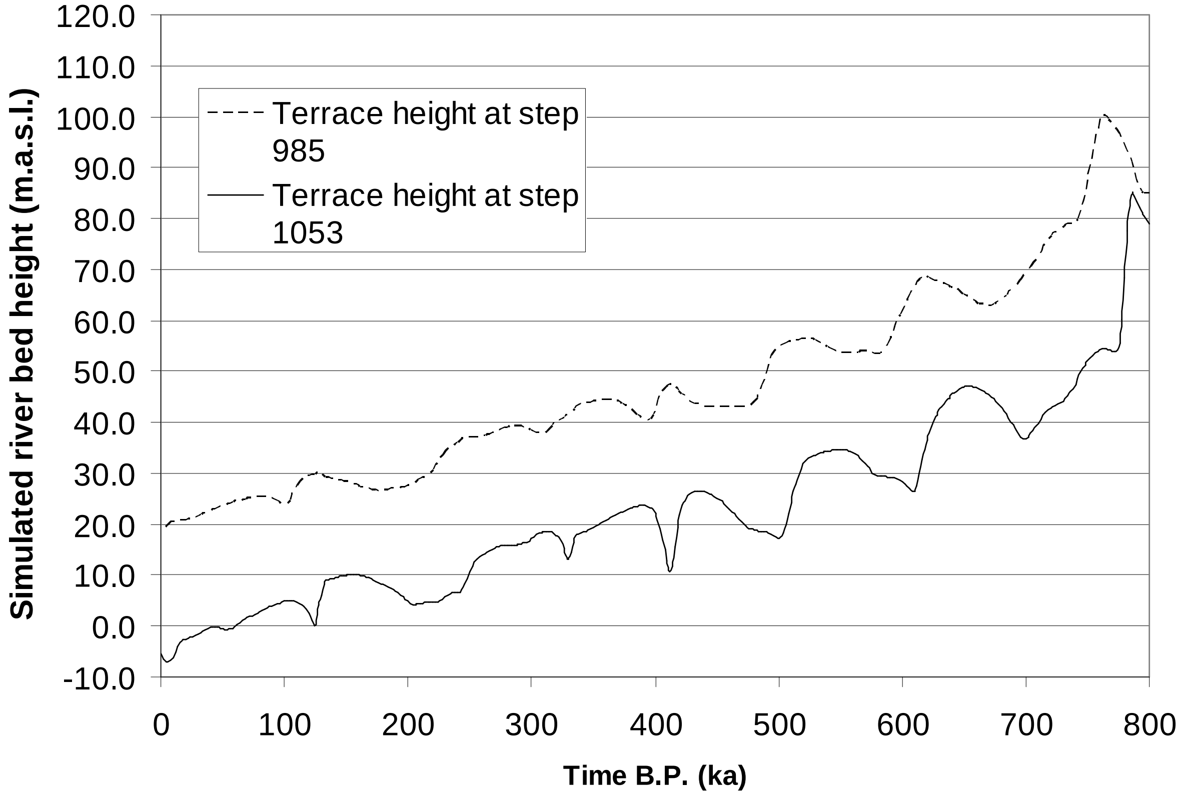

Figure 22. Simulated terrace heights at steps 985 and 1053 for scenario 2.

9.2.4 Scenario 3 Glacial aggradation

24 model runs were performed. Most parameter combinations within the X-field gave similar results, so we can say this scenario is quite balanced. A combination of *k-sed* 11* 10^{-11} and *Dis* 60 km gave the best results. This results in a simulated profile on average situated 7.5 m below the initial profile. The simulated profile has a concave form, suggesting a graded profile development. In the upstream part of the profile, there is slightly too much erosion and around the Bierzo a bit too much deposition. This same pattern has been observed for the former scenarios as well, suggesting that uplift rate in the hinterland could even be a bit higher. Deposition at the foot slopes of the hinterland in the Bierzo is attributed to the form of the initial profile. There are 2 knick points at 88 km and 108 km, after which river gradient decreases significantly. These are the ideal places for sediment to accumulate, so it is probably not possible to perform a model run without sedimentation in this area. Overall, the form and height of the simulated profile are in agreement with the contemporary profile (Figure 23).

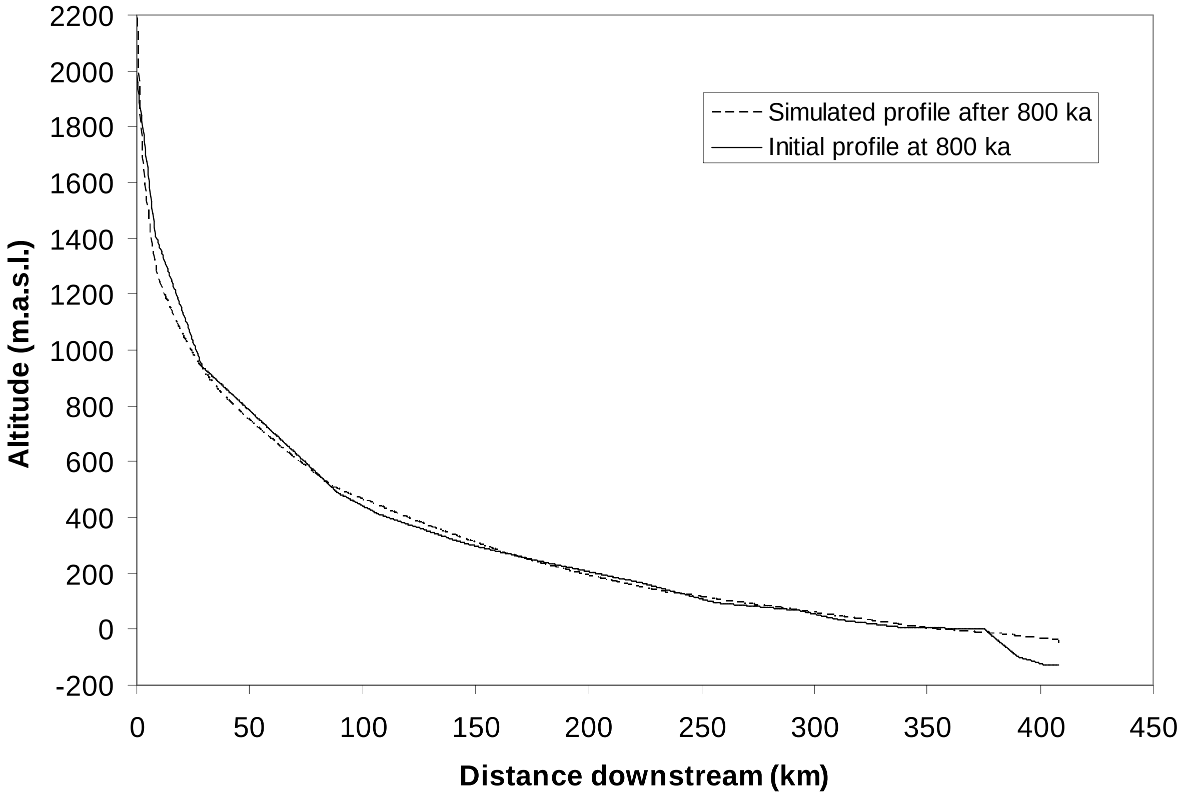

Figure 23. Initial profile at 800 ka and simulated profile after 800 ka for scenario 3.

Sediment yield was 46.9 m and 80.3 m for steps 985 and 1053 respectively.
The simulation generated 8 cycles of sedimentation and erosion that move upstream to 280 km along the profile. By linking the terraces to glacials, in theory 8 terraces fit within the time-frame of 800 ka. This agrees with the simulation outcome.
In the Bierzo sedimentation is dominant during the first half of the run and erosion dominates the second half. Just like in the other scenarios, sedimentation events at 170 km, 272 km and 400 km are found during model initialisation (Figure 24).
The simulated terrace heights at step 1053 (Figure 25) are found at the following heights: 8.1 m (7.3 m), 12.8 m (13.4 m), 21.7 m (24.5 m), 28.3 m (31 m), 32.1 m (40.1 m), 40.2 m (52.9 m), 52.8 m (66.5 m) and 58.9 m (76.3 m). The link with real world terraces is visible for the terraces up to 28.3 m. It is not a strong link, however because the remaining terraces do not agree at all. If we alter the terrace chronology and add the minimum (13.4 m) and maximum height (18.9 m) of the real world T1 as 2 separate terraces, then the chronology becomes

much better: 8.1 m (7.3 m), 12.8 m (13.4 m), 21.7 m (18.9 m?), 28.3 m (24.5 m), 32.1 m (31 m), 40.2 m (40.1 m), 52.8 m (52.9 m) and 58.9 m (66.5 m). The correlation is tentative, especially because T1 was split up. We saw that this terrace rises away from the Miño and attains a minimum and a maximum height of 13.4 m and 18.9 m, respectively. Up till now the terrace was assumed to be one terrace, but the correlation of the minimum and maximum height with 2 simulated terraces suggests that T1 could in fact consist of 2 terraces.

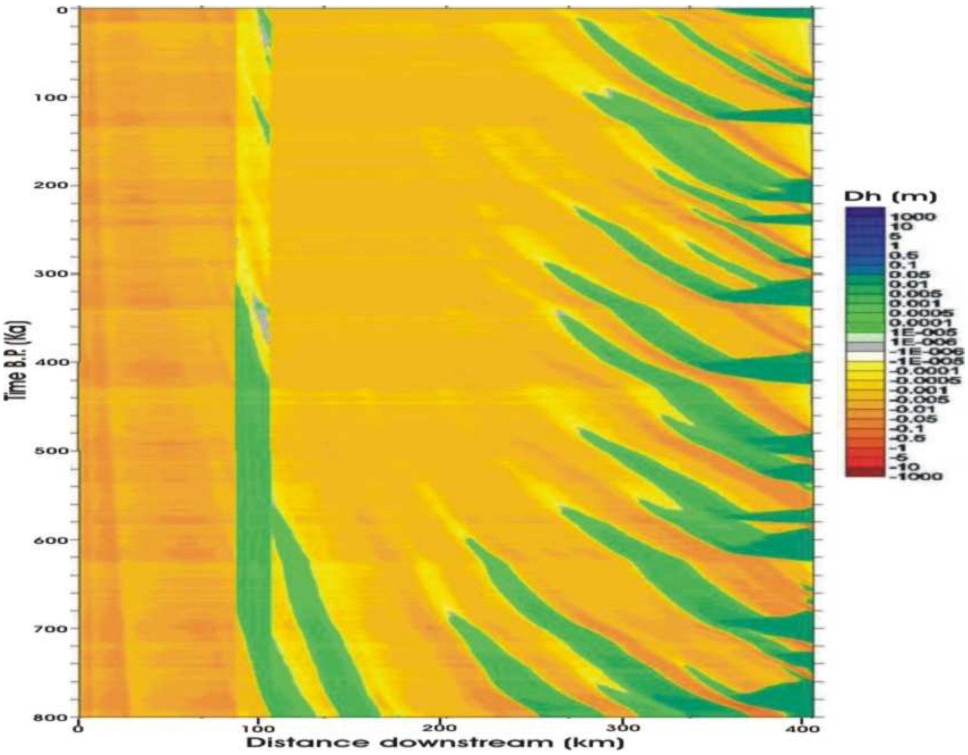

Figure 24. Profile Evolution Map for scenario 3.

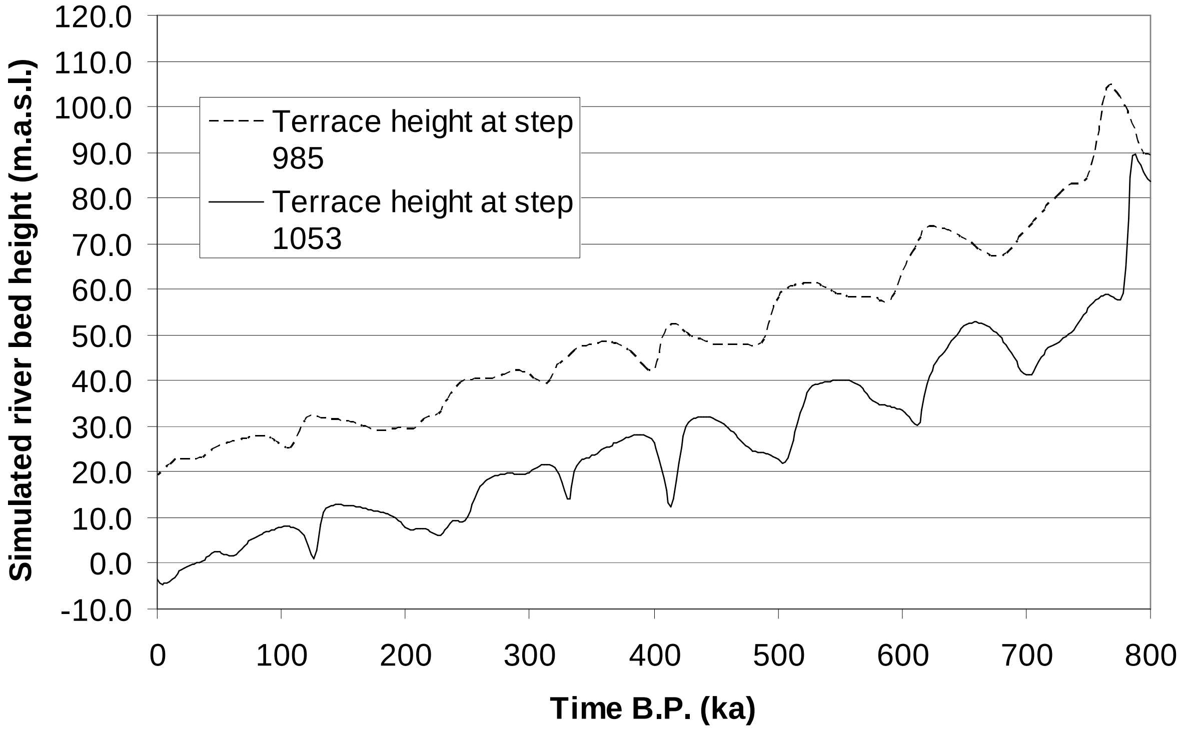

Figure 25. Simulated terrace heights for scenario 3.

9.2.5 Scenario 4 Marine terraces

24 model runs were performed to obtain the best combination of parameters. The best combination of parameters proved to be *k-sed* 12 * 10^{-11} and *Dis* 50 km. For most runs it was possible to generate a graded profile as in agreement with criteria 1 and 2. The simulated profile is situated 7.8 m below the current profile. There is slightly too much deposition between 80 km and 150 km, and the upstream part of the profile experiences too much erosion, but in general a very plausible profile is generated. See Figure 26. It was also possible to generate sufficient sediment at steps 985 and 1053. At step 985 an amount of 48.3 m was simulated and at step 1053 this was 89.5 m.

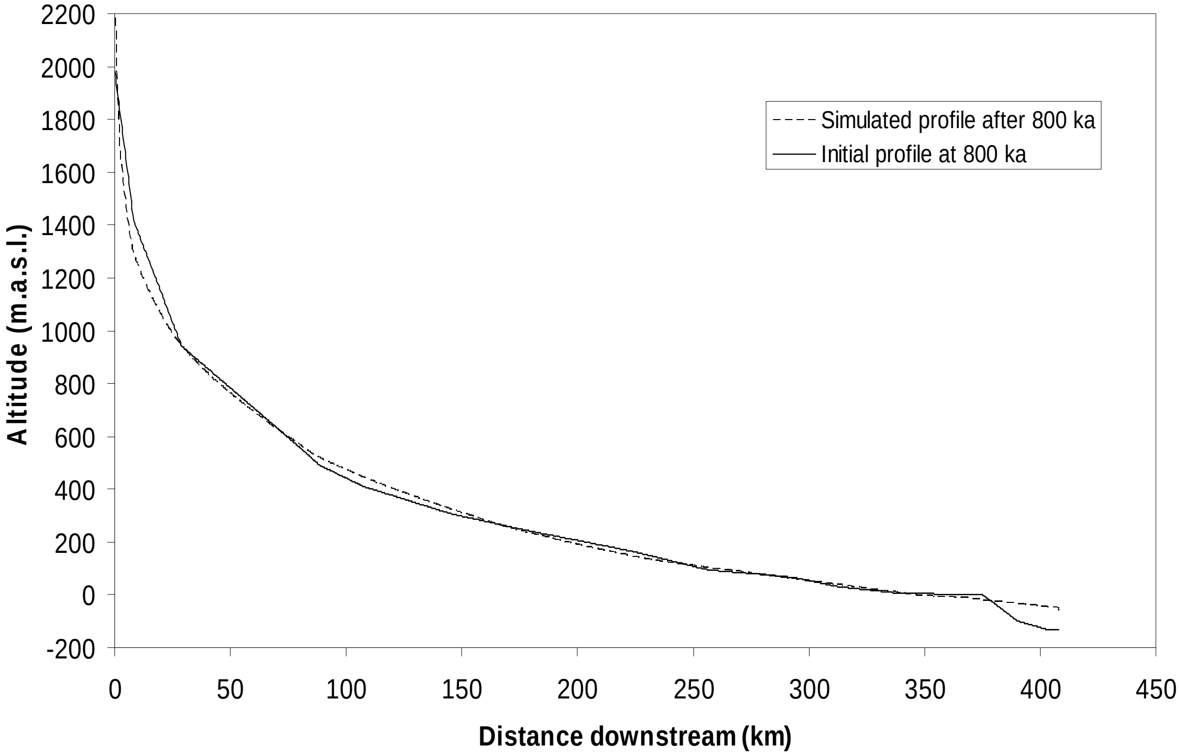

Figure 26. Initial and simulated profiles for scenario 4.

In total, 8 principal phases of alternating erosion and deposition were simulated. This agrees with the assumptions made as the uplift curve (Figure 6) suggested that a total of 8 phases was to be expected.
The sedimentation phases reach inland up to 280 km along the profile. This is in agreement with field evidence as discussed for the previous scenarios (Figure 27).
In the Bierzo sedimentation is dominant during the first half of the run and alternating cycles of erosion and deposition dominate the second half of the model run. Sedimentation events at 170 km, 272 km and 400 km are found during model initialisation.
The reconstructed terraces at step 1053 are found at 0.3 m, 5 m, 14.2 m, 20.5 m, 21.7 m, 29.4 m, 38.4 m and 48.6 m. Those heights are considered less realistic as the simulated heights for the other scenarios, as 6 of the terraces are found below 30 m (see Figure 28).

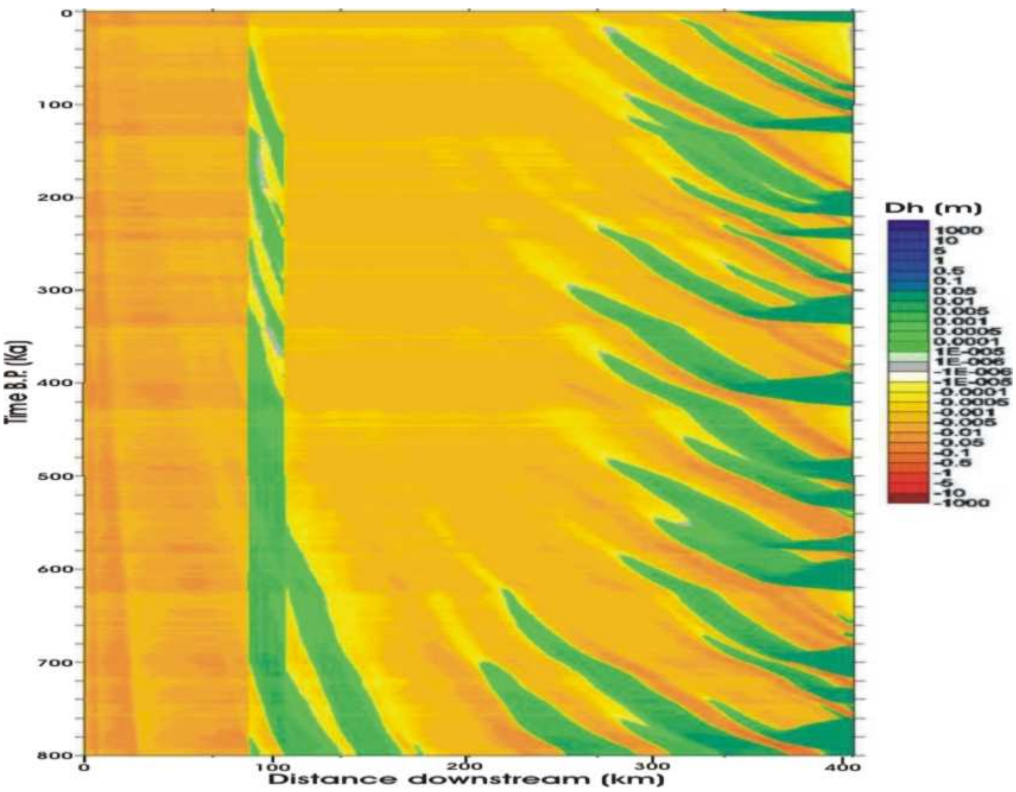

Figure 27. Profile Evolution Map for scenario 4.

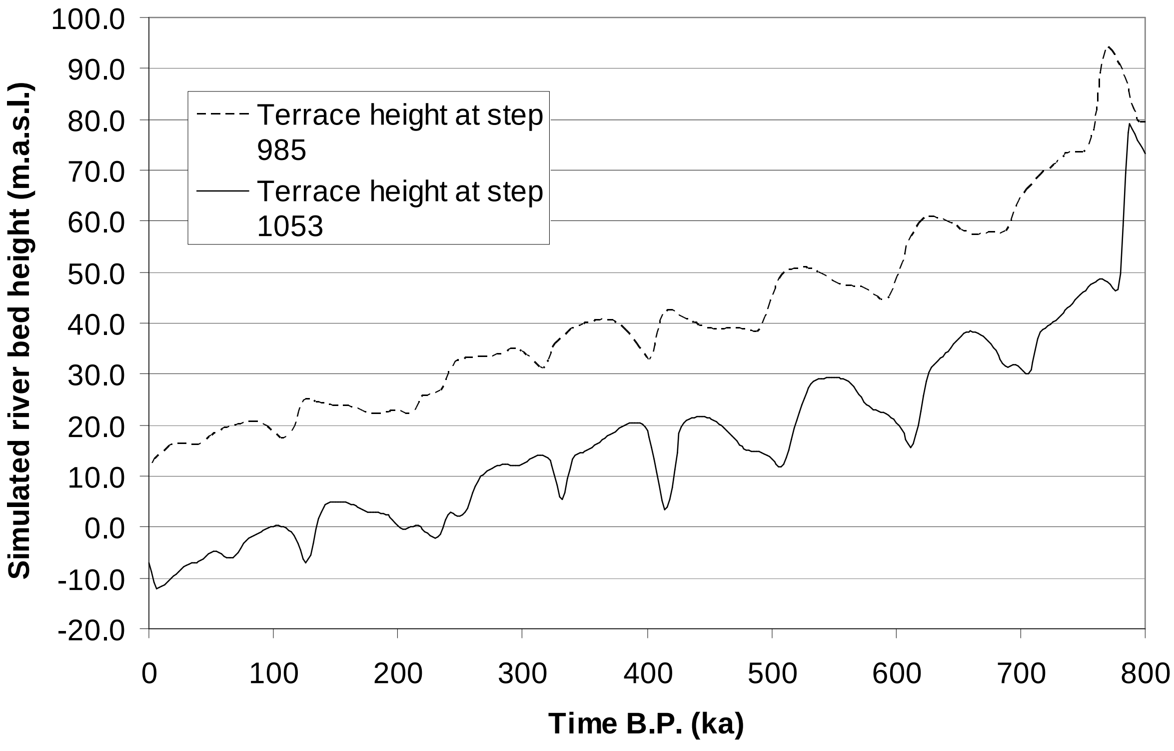

Figure 28. Simulated terrace heights at steps 985 and 1053 for scenario 4.

9.2.6 Scenario 0 No uplift

This scenario is discussed last because knowledge of the other scenarios is needed to understand the outcome of scenario 0.
Generating plausible results proved to be impossible for this scenario. 34 runs were made, but each run resulted in an unstable profile. In each of these cases, the hinterland was severely eroded whereas there was too little erosion or too much sedimentation in the middle part of the profile. The profile was more realistic for Galicia, but close to the Atlantic Ocean there was once more too much erosion. It was therefore not possible to comply with criteria 1 and 2. The best approximation is a combination of *k-sed* 12 * 10^{-11} and *Dis* 30 km. That yields a simulated profile situated on average 11.3 m below the initial profile (Figure 29).

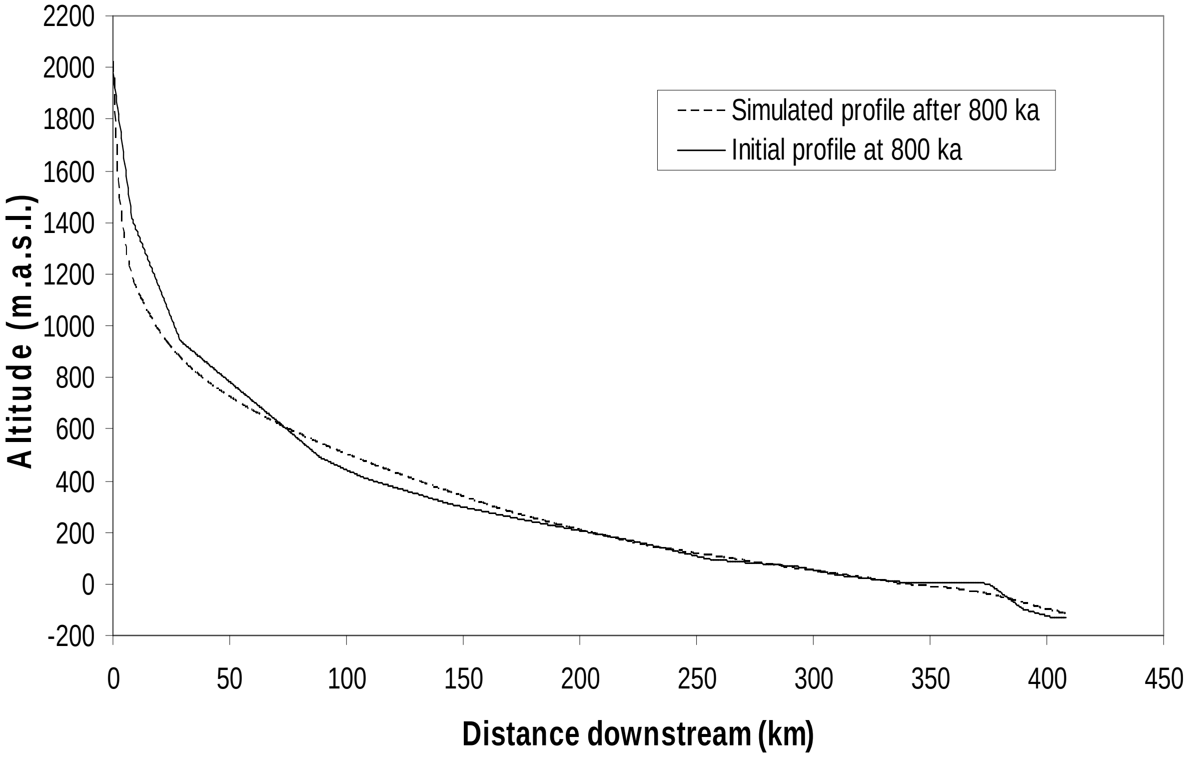

Figure 29. Initial profile at 800 ka and simulated profile after 800 ka for scenario 4.

Total amount of sediment generated for step 985 was 39.4 m and for step 1053 106 m. These amounts are in agreement with criterion 3.
Figures 30 and 31 show that there are 10 alternating phases of erosion and deposition. These phases form 8 terrace levels at step 1053 with the 9th Holocene level being under construction. The depositional phase around 390 ka is found at a higher height than the earlier level at 440 ka, meaning that the latter level is buried beneath the 390 ka terrace. So these levels form one terrace instead of 2 separate terraces. Sea level influence clearly diminished upstream as is seen at the terraces at step 985. Here only 6 terrace levels are generated.
Sedimentation phases start at the land-sea transition and moving upstream to 290 km. The latter agrees with field evidence as the sedimentary wedge is found up to at least 300 km, but the number of simulated terraces is too much. This means that criterion 4 is fulfilled, but criterion 5 is not. Further upstream in the Bierzo and in the transition between Bierzo and Leonese mountains a number of sedimentary phases are found as well. These take place during the first 200-300 ka of the model run, but are not found afterwards. The continuous sedimentation in the Bierzo as registered in other scenarios is clearly not visible. It is therefore not unlikely that the deposition during the first part of the model run is the result of an initial excess in sediment that is deposited where the river profile decreases in gradient. In

this scenario the Bierzo does not experience any form of uplift or subsidence, so its basin-like structure cannot play a role in capturing sediment. Its geographical position in front of the foot slopes should therefore be the main cause.
Figure 31 shows the reconstructed terrace heights. Because there is no tectonic uplift in this scenario, the uplift factor is not added. First of all, we see that in this scenario too there is a clear disparity between the curves for steps 985 and 1053. Sediment bodies for step 985 are situated ~30 m above the sediment bodies of step 1053. Secondly, we see that the simulated height by no means approximates the real terrace heights. At step 1053, the major part of the sediment bodies is found below the present Miño water table at -16.9 m, -16.7 m, -12.1 m, -9.2 m, -4.1 m, -1.9 m and -1.1 m. The remaining bodies are found at 8.2 m and 21.1 m. Even at step 985, 6 sediment bodies are situated in between 0 and 30 m. In reality, only 4 terrace levels are found up to 30 m height and the remaining ones up to 95 m. Also, the simulated lower terraces show almost no difference in height, whereas in the field there are clear scarp faces of up to 10 meters height. All in all, the majority of criteria cannot be fulfilled. This lead to the conclusion that, under the given assumptions and criteria, uplift is a prerequisite in simulating a longitudinal profile and terraces that agree with reality.
Table 7 gives a summary of the most important results for all scenarios.

In this context, the outcomes of scenario 0 are considered surprising in another way as well. The current train of thought is that terraces cannot form without an uplift component (see for instance Bridgland et al., 2004; Veldkamp & Van Dijke, 1998; 2000), but scenario 0 clearly generates 8 to 9 terraces at step 1053. The simulated terraces have small scarp faces and most of the terraces are found below the Miño water table, but they are still terraces. Once more, the short continental shelf and steep submarine gradient of the river are probably the driving factor. The steep gradient favours a rapid and aggressive incision during periods of low sea level. When a subsequent rise in sea level does not equal the former high sea stand, renewed aggradation will take place below the former stack of interglacial sediments instead of on top. In theory, a renewed sea stand of up to 0 m could erase all previously build terraces, but apparently this does not always happen. Sea level input are actually modelled estimations with a certain standard error (Bintanja, et al., 2005). The Eemian sea level high stand that was estimated at ~3 m a. m. s. l. in Galicia (Trenhaile et al., 1999), is modelled as a 0.3 m high stand by Bintanja et al., (2005). That means that in reality, the Eemian land-sea transition was found further inland and consequently, a higher base-level existed. It is therefore not unlikely that a higher Eemian sea level high stand triggered fluvial deposition on top of the Miño terraces that were formed earlier on. That would erase the lower terrace levels, but would probably still leave the higher terrace levels intact.

Overall, the outcomes show that in an area with a short or steep continental shelf in combination with a high terrestrial relief at short distance from the ocean, terraces can form. All of the already mentioned works of Veldkamp (Veldkamp & Van Dijke, 1998; 2000), Tebbens (Tebbens et al., 2000; Veldkamp & Tebbens, 2001) and Bridgland and Maddy (Bridgland et al., 2004) focused on the NW European fluvial systems surrounding the North sea basin. This basin is a very shallow basin with a gentle gradient. During glacials, the course of these rivers is lengthened hundreds of kilometres, as for the Meuse (Tebbens et al., 2000). Drops in sea level therefore do not lead to an aggressive down cutting of the fluvial system. On the contrary, they lead to gentle changes in the fluvial system that are registered in fluvial terraces on a millennia-scale basis (Van den Berg, 1996). The question therefore arises if, and to what extent, fluvial systems in a basin setting and systems in areas with short, steep continental shelves can be compared.

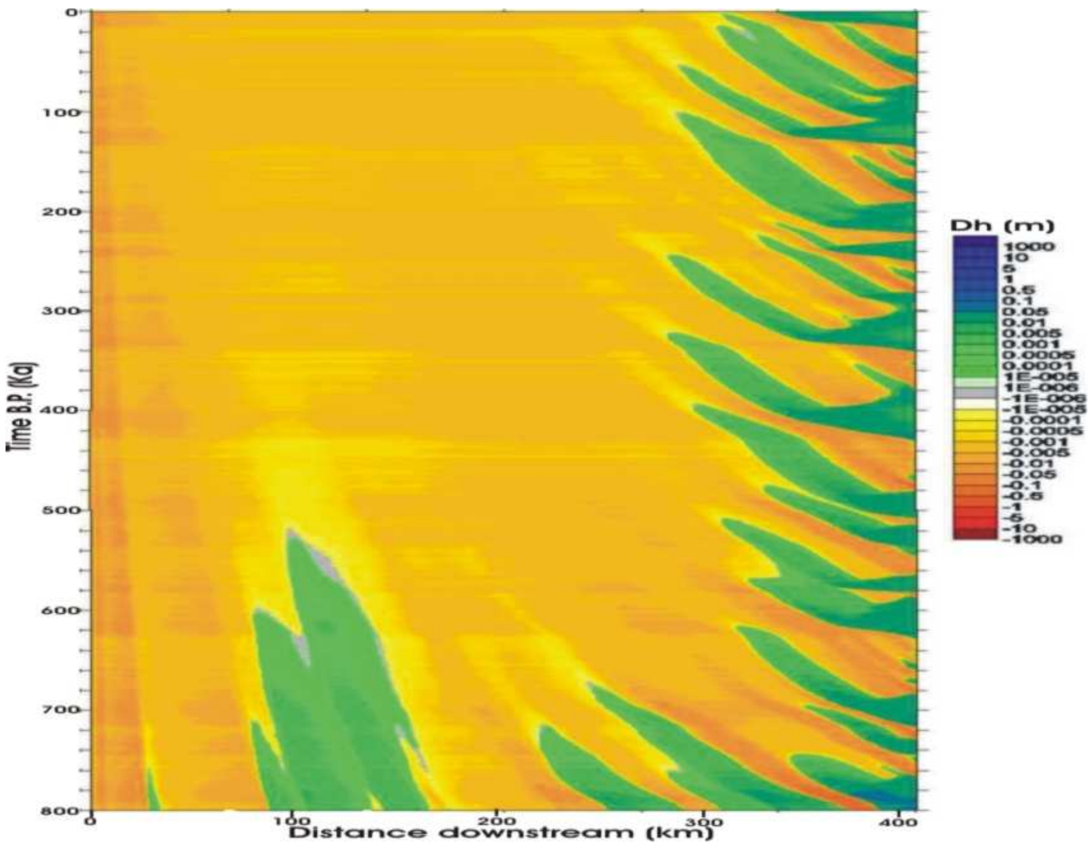

Figure 30. Profile Evolution Map for scenario 0.

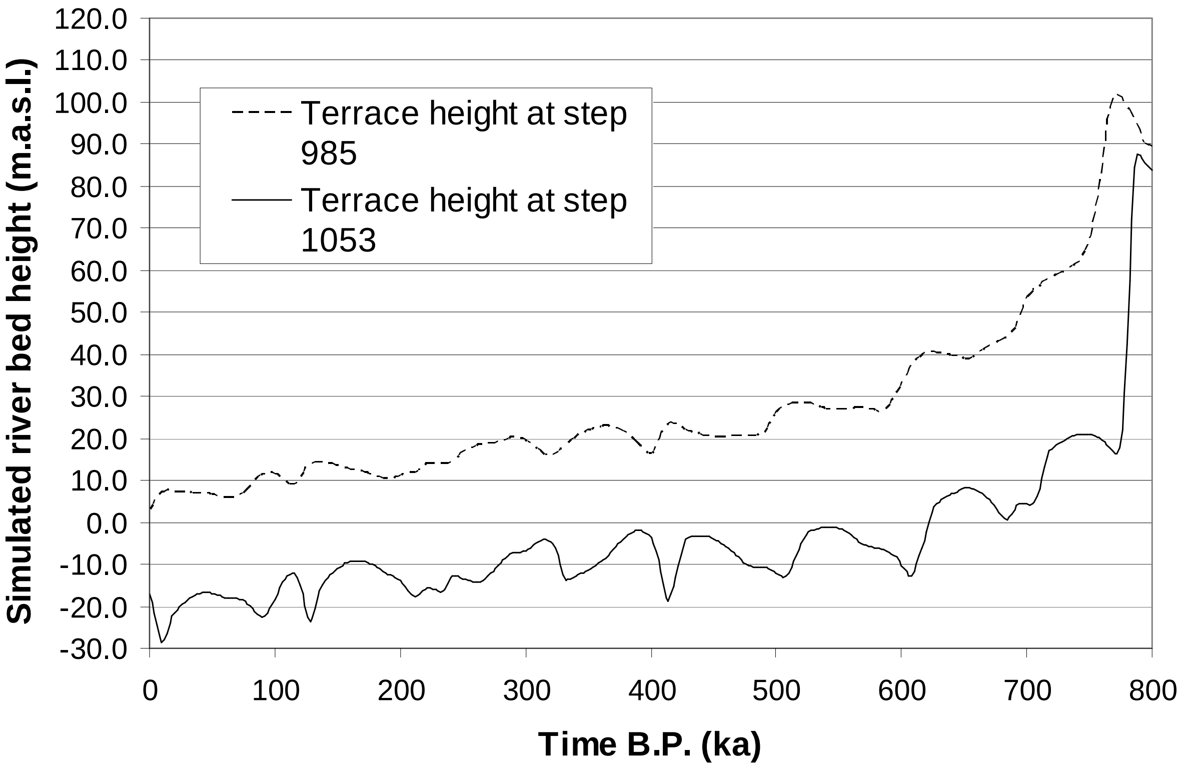

Figure 31. Reconstructed fluvial terraces at steps 985 and 1053 for scenario 0.

Table 7. Summary of the most important results for each scenario.

	Scen 1a	Scen 1b	Scen 2	Scen 3	Scen 4	Scen 0
k-sed *10^{-11} and Dis (km)	11 and 60	10 and 70	10 and 60	11 and 60	12 and 50	12 and 30
Profile (m)	-5.6	-7.7	-1.7	-7.5	-7.8	-11.3
Sed at step 985 (m)	47.1	41.4	39.4	46.9	48.3	39.4
Sed at step 1053 (m)	79.6	66.3	66.5	80.3	89.5	106
Sed wedge (km)	272	272	285	280	280	290
# terraces	8	8	8	8	8	10
Terrace heights (m.a.s.l.)						
T0 (field observation 7.3)	10.5	10.3	5.1	8.1	0.3	-16.9
T1 (13.4-18.9)	15.8	16	10.1	12.8	5	-16.7
T2 (24.5)	25.3	27	18.6	21.7	14.2	-12.1
T3 (31)	33.3	33	23.6	28.3	20.5	-9.2
T4 (40.1)	38.7	38.1	26.4	32.1	21.7	-4.1
T5 (52.9)	45	43.6	34.6	40.2	29.4	-1.9
T6 (66.5)	56	55.6	47	52.8	38.4	-1.1
T7 (76.3)	61.4	62.7	54.4	58.9	48.6	8.2
T8 (84)						21.1

Profile refers to the mean deviation of the simulated profile with respect to initial profile
Sed at steps 985 and 1053 refers to amount of sediment deposited
Sed wedge refers to how far upstream the sedimentary wedge is found.
 # terraces refers to the amount of terraces simulated
Terrace heights refer to the simulated terrace heights. For ease field observations are added.

Chapter 10 Interpretation of modelling results and discussion

The outcomes of the different scenarios are similar. Therefore, these results are discussed together with the context of terrace formation of the lower Miño. The most logical scenario follows automatically, although picking the best scenario is only a help and not the goal in itself.

10.1 Eustatic control on terrace formation

Figure 32 compares the Profile Evolution Map (PEM) of scenario 2 against sea level oscillations during the past 800 ka. It is clear that deposition starts during periods with high sea level. Sediment is first laid down in the shape of a delta as shown by the dark green triangular shapes in the PEM. The delta is found in between ~375 and 408 km and does not migrate much through time. We see that during sea level low stands the delta is eroded as the Miño lengthens its course and starts to incise. When sea level rises again, a new delta forming phase starts. This is perfectly in line with Tebbens et al. (2000 and authors therein) who observed the same pattern of change for the Meuse delta system.

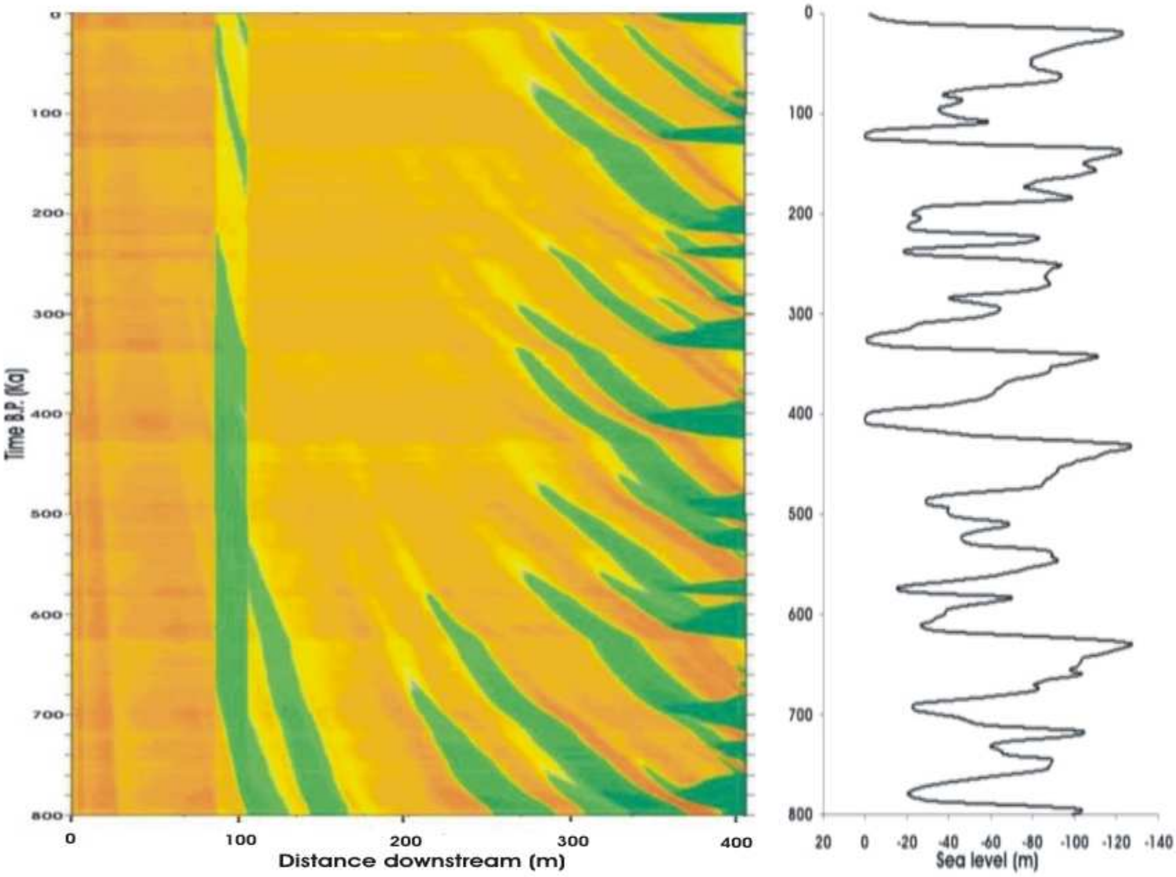

Figure 32. Profile Evolution Map of scenario 2 compared against sea level data of Bintanja et al. (2005).

It is proposed that during interglacials, a coastal prism slowly migrates upstream in the form of a backfilling sedimentary wedge, as more sediment is delivered. In theory instead of backfilling, down filling could be the main process for sediment delivery. There are strong indications that this is not the case for the lower Miño. First of all, down filling deposits should wedge out to both sides whereas backfilling sediments only wedge out downstream (Schumm, 1993). As we have seen, the latter is the case in the lower Miño and even forms part of the calibration criteria (criterion 3). Then, in the case of down filling, the coarsest sediments are found upstream and the finest downstream. In both cases the sediments should experience a coarsening upward and a clear difference in grain size and mineralogy due to progressive head ward erosion in the hinterland (Schumm, 1993). In the lower Miño, most enclosures show a consistency in mineralogy and grain size, and in not a single case a coarsening upward sequence was found. On the contrary, all enclosures either showed a homogenous stack of gravel or a stack of gravel with a meter of fine silty clayey sediment on top. These characteristics are discerning for the presence of a backfilling deposit (Schumm, 1993).

This shows that glacial aggradation, as hypothesised in scenario 3, is unlikely. Curiously enough, the backfilling process takes up more than 100 ka to reach the 280 km point along the profile. This implies that, when sea level drops again during a glacial, aggradation upstream as triggered by an earlier sea level high stand, continues. This complex response was also observed by Tebbens et al. (2000) for the lower reach of the Meuse. They found that at the beginning of the Weichselian, the lower reach was already incising due to a drop in sea level, whereas the more upstream part was still aggradating because of the Eemian high stand. The more upstream reach lagged 14 ka behind the lower reach of the Meuse (Tebbens et al., 2000). In another modelling exercise, Veldkamp & Tebbens (2001) even found the upstream part of the Meuse near the hinge line to lag 20 ka behind sea level fluctuations. Merritts et al. (1994) also found that sea level high stands trigger the formation of a backfilling sedimentary wedge. But in their case the wedge migrated upstream in a short time period and did certainly not protrude upstream during sea level lowering. Merritts et al. (1994) showed that low sea level stands triggered incision of the depositional wedge. This is in agreement with the modelling results, although the timing is out of phase with these processes.
Most likely the steep gradient of the submarine part plays a major role. The gradient causes that a larger volume of sediment is needed to level off the large profile difference, and consequently more time is needed to provide sufficient sediment bulk for the sedimentary wedge to start migrating upstream. As we have seen before, data for the currently submarine Miño is not available and therefore the current topography of the ocean floor was taken as an analogue. The cliff that is visible at 375 km along the profile (Figure 8) is cut through within the first 30 ka of a random model run, up to the point that the river is graded to base level (sea level) again. This indicates that the palaeo-profile has likely a gentler gradient as well. The same observations were done already in Chapter 10.1 where the height difference between terraces at 2 steps along the profile was attributed to a too steep submarine profile. Schumm (1993) discusses that the effect of base-level depends on the inclination of the shelf compared to the stream gradient. A sedimentary wedge can only form when the slope of the continental shelf is gentler than the one from the river profile. This happens because the river channel cannot compensate for this decrease in gradient by internal adjustments (change in channel pattern). On the other hand, when the slope of the continental shelf is steeper than the gradient of the river channel, a river will first react by increasing its sinuosity. When the shelf slope increases even more, the river can no longer compensate by increasing its sinuosity and will start to incise. The channel can widen up and become a braided system instead before the channel is finally capable of changing its shape and roughness (Schumm, 1993). In the lower Miño, the large amount of point bar systems found in enclosures for various terrace levels, directs towards the presence of a meandering system (Nicols, 1999). Also, the modelling exercise clearly demonstrated that a backfilling sedimentary wedge is formed. These observations in combination with the work of Schumm (1993) suggest that 800 ka ago, the submarine part of the Miño profile was indeed much more gentle than assumed. This is not surprising, considering the fact that the Miño-Sil system is likely a very old system and had ample time to deliver sediments onto the probably once steep, continental shelf. Through time the shelf gradient was effectively reduced up to the point that the Miño could accommodate the formation or a backfilling sedimentary wedge.

The PEM shows that depositional events take place up to 272-280 km before incision phases take over. These sea level-triggered incision phases extend upstream for at least another 40 km, and are alternated with more severe incision phases during glacial low stands. This could indicate the formation of strath terraces. In the Mendocino Triple Junction, the backfilling wedge graded into strath terraces further upstream (Merritts et al., 1994). Indeed, throughout the Miño, strath terraces are found that fall within the modelled area of eustatic dominion (Yepes-Temño, 2002, see Table 5). The modelling results indicate that base-level changes play a role upstream of the sedimentary wedge. This confirms the observations of Merritts et al. (1994) who suggested that in areas where base-level fall is caused by long-term tectonic uplift, a stream may continue to down cut even during a sea level high stand. A former sea level high stand may cause knick points to migrate slowly upstream, thus creating a considerate time-lag of upstream reaches to base-level response.
Of course, the strath terraces could also be the result of solely uplift in combination with climatic changes, or simply eroded fill terraces. With the current data set it is not possible to verify exactly how far upstream eustacy is a dominant factor in terrace formation.

The 100 ka cycle of glacio-eustatic control on terrace formation is confirmed by the number of simulated terraces and by the number of terraces found in the field. In all scenarios, 8 terraces are simulated which almost agrees with the number of major sea level high stands during the past 800 ka. Contrary to expectations, the model does not simulate terrace formation during the Holocene. The PEM does not display the formation of a sedimentary wedge and in the terrace height curve no terrace forms. That implies that the Holocene terrace is still under construction. Thus, the number of sea level high stands fits the number of simulated terraces. On basis of this information, scenarios 1a and 1b are rejected and leave us with scenarios 2 and 4, even though the predicted terrace heights of scenario 1a/b agree much better with reality then the ones of scenarios 2 and 4.
The peak around 786 ka is most likely an artefact of model initialisation because its height and form do not fit the pattern of the other terraces. Also, the peak occurs *before* the rise in sea level, while all other terraces are found as a result of, and thus *after* a rise in sea level. This peak is therefore not considered as a separate terrace.
The reconstructed terrace height curves show that even minor sea level fluctuations are recorded in the sedimentary record. These are visible as small incision and depositional events within the more dominant 100 ka cycles. That shows the sensitivity of the coastal fluvial record to sea level changes. The closer to the ocean, the more sensitive the system is to eustatic control. The terrace height curves in Chapter 9 clearly show that the amplitude for each 100 ka cycle is larger at step 1053 than at step 985. Especially the incision intensity diminishes further upstream. This elegantly demonstrates the fading effect of eustatic control on terrace formation more upstream of the river system.

10.2 Climate

The model was run with the hill slope sediment supply parameter switched off and with a linear transformation whereby more discharge automatically generates more sediment. Climate input is therefore highly linear. Higher sediment fluxes are generated during interglacials when a wet, temperate sea climate prevails. Attribution of sediments during glacials is minimal as neither overland sediment fluxes nor fluvial fluxes dominate. The PEM shows that during glacials, erosion dominates in the downstream reach. This shows that predominantly interglacial sea level high stands in combination with increased interglacial sediment fluxes are the main factor for terrace formation in the lower Miño. That is another explanation why the backfilling process takes so long: when the system changes to glacial conditions again, sediment delivery diminishes and consequently the upstream migration of the sedimentary wedge slows down.
In the upstream part between 0 and 100 km a reverse situation exists. Erosion is dominant throughout time, but different climate cycles clearly show up in the PEM in the form of

horizontal alternating yellow/orange bands. During interglacials erosion is more severe than during glacials. This trend continues, albeit less extreme, all the way downstream to where the sedimentary wedge is found. The Bierzo thereby acts as an effective sediment trap. This is firstly attributed to its geographical position at the foot slopes of the Leonese mountains as the stream gradient becomes less. Then there is the tectonic input for the Bierzo: while both the hinterland and Galicia are uplifting, tectonic movement for the Bierzo was set at zero. In this way the basin-like properties of the Bierzo were simulated in the 2D model. Although not entirely realistic, the simulation still shows that the Bierzo experiences an almost continuous infill, even when there is not uplift. The Bierzo is known to contain several hundreds of meters of sediment (Andeweg, 2002), so it is likely that during the simulated time period this was also the case. Because of these assumptions, a more precise reconstruction is not feasible.
The pattern of interglacial erosion and less erosion during glacials can be linked as well to higher discharge dynamics during interglacials and lower discharges during glacials. In the hinterland of other catchments, for instance the Meuse (Van den Berg, 1996; Tebbens et al., 2000), the Carpathians (Starkel, 2003) or the Upper Thames (Stemerdink, 2007) glacials register more sediment supply as permafrost and absence of vegetation trigger overland flow. Because the Leonese mountains experienced (peri) glacial conditions during the glacials (Garcia-De Celis, 1997), sediment dynamics in the upstream part of the Sil are not considered entirely realistic. They are simply the result of the model input whereby hill slope sediment supply and vegetation cover were neglected. A more complex response between the upstream and downstream reaches of the basin is therefore likely, as suggested by work in other river catchments (Veldkamp & Tebbens, 2001). This could for instance result in less sediment transport downstream during interglacials, and more sediment delivery during glacials, which in turn would influence or even speed up the build-up of the backfilling sedimentary wedge through time.

The PEM shows that the effects of base level change are large, but do not rejuvenate the entire system. Schumm (1993) states that “total rejuvenation of the drainage system is not expected, although the effect will be greatest where base level change is great, incision rapid and the rivers are confined.” Schumm (1993) furthermore explains that rapid incision can be triggered by a high amount of discharge in combination with a narrow valley. All these factors are present in the Miño-Sil system and stress the importance of discharge dynamics.

10.3 Bedrock uplift

Sea level changes and sediment flux are not the only steering factors for terrace formation. The outcomes of scenario 0 have shown that the terraces in the lower Miño cannot be formed at representative heights without an uplift component. The other scenarios generate more realistic terrace heights. The question is how dominant the uplift factor exactly is in terrace formation. Figure 33 shows the reconstructed terrace levels for all 6 scenarios.

Each scenario has different uplift rates and it would therefore not be unlikely to see differences in terrace formation. But what is shown is that the amount and timing of the generated terraces is almost exactly the same for all scenarios. Even if there are slight variations in timing, then these are caused by differences in the parameter *Dis* between scenarios. The only real visible difference is terrace height, so differential uplift only favours the altitude at which terraces are ultimately formed. By linking the terraces to different periods, a shift in timing and hence, a different total uplift over 800 ka was realised for each scenario.

Total uplift for all scenarios is given below in ascending order of total uplift:
Scenario 0: 0 m.
Scenario 4: 69.4 m.
Scenario 2: 75.2 m.
Scenario 3: 79.8 m.
Scenario 1: 82.1 m.

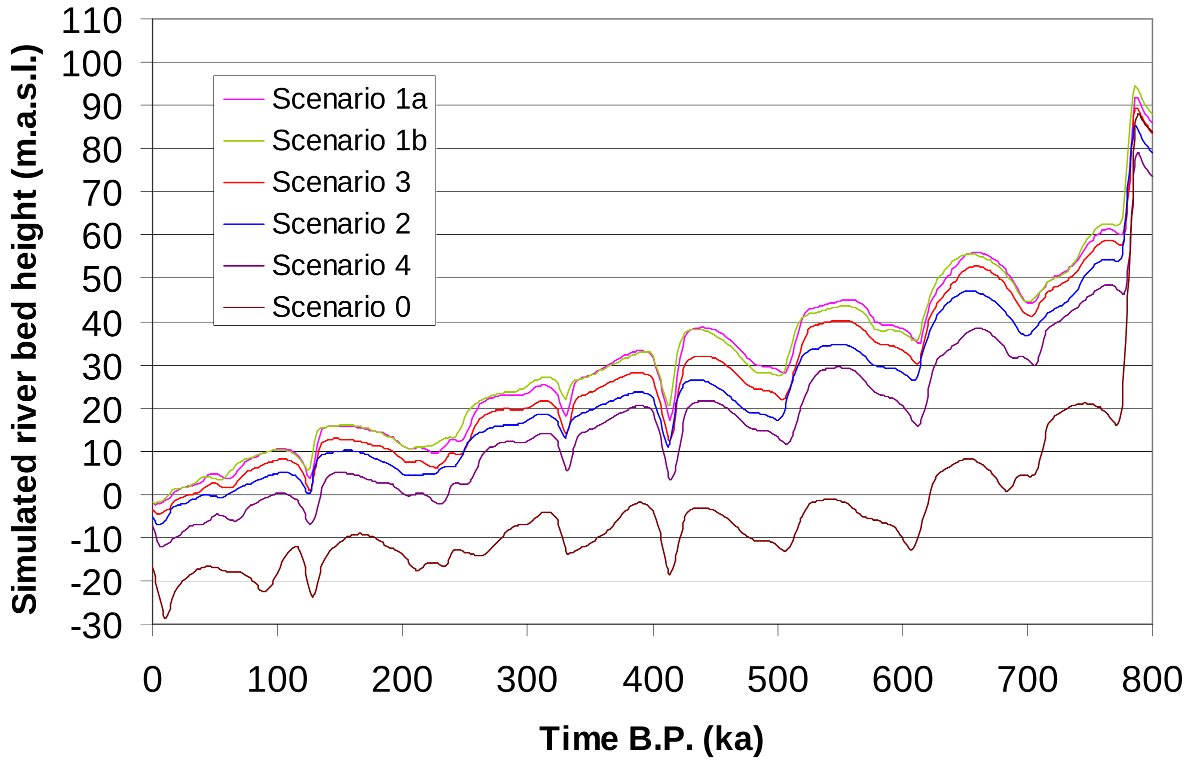

Figure 33. Reconstructed terrace height curves at step 1053 for all 6 scenarios.

When looking at the figure, exactly the same order is seen. Scenario 0 is found at the lowest place in the figure, followed by scenarios 4, 2, 3 and 1. That suggests that total amount of uplift is the main cause for the differences between each scenario and not so much differential uplift rates between time periods within a scenario (see Figure 7). Setting the uplift rate at 0 m for the time-span 0-116 ka in scenario 4, did not overly influence the simulation. It is therefore not possible to confirm or reject the presence of tectonic stability during this period.
The idea that total uplift is important is confirmed by comparing scenarios 1a and 1b. There is hardly any difference between scenario 1a and 1b, even though scenario 1a uses differential uplift rates and scenario 1b a mean uplift rate. The small difference that does exist is attributed to slightly different total uplift rates. For scenario 1b an older data set with rounded values was used and for 1a not. That created a small, but negligible total amount of uplift.

The mean calculated uplift rates vary between 0.09 m/ka (scenario 4) and 0.10 m/ka (scenario 1). These rates fall exactly within the uplift range predicted by Cabral (1995) for the Portuguese Miño region (see Section 7.1.1). Furthermore, Veldkamp & Van den Berg (1993) found that the preservation potential for alluvial terraces is greatest for areas with a typical uplift of 0.08 to 0.11 m/ka. This could explain why the lower Miño terraces are so well preserved.

The PEM shows that the depositional wedge extends up to 272 to 280 km, depending on the scenario. This is (375-272)/375 =27 percent of the total length of the Miño profile. Merritts et al. (1994) calculated that the wedge in their fluvial system took up 31 percent of total stream length. It could be that tectonics governs the extent to which a sedimentary wedge migrates upstream. Uplift rates in the Mendocino Triple Junction are around 0.8-1.1 m/ka (Merritts et al., 1994). That is a factor 10 higher than the assumed uplift rates for the Miño-Sil basin. So if uplift were the main driver for sedimentary wedge formation, this surely would have generated a significance difference between sedimentary wedge protrusion in both systems. But what we see is that in both systems about a third of the river profile is occupied by this wedge. These figures show that eustatic changes indeed extend their influence far upstream and may overrule tectonic uplift.

Apart from uplift, terrace height is also governed by the parameters *k-sed* and *Dis*. A small change in one of the 2 causes more erosion/incision or more sediment yield. The height differences between curves in Figure x are therefore also dependent on these parameters. Overall, we see that uplift is needed to create terraces at a realistic height, but uplift does not control the amount of terraces, or timing of terrace formation in the lower Miño. Uplift is overruled by sea level changes in terrace formation. Sea level changes and sediment flux are therefore considered the main drivers.

The modelling exercise generated 8 terrace levels because there were 8 major interglacial/glacial cycles during the past 800 ka, not counting the Holocene. We have seen that not all simulated terraces match the real terraces in height. The lowermost terraces do match the existing terraces, but the middle and higher terraces do not. A likely source of error could be the unrealistic submarine part of the Miño profile as explained before. Another explanation could be that not all terrace levels were found during field work. In a time window of 800 ka, the model is expected to generate in almost all circumstances 8 terrace levels because sea level fluctuations are the dominant factor. We have seen that the formation of terraces in itself is not very sensitive to tectonic input. It is therefore possible that more terraces are present and that I have unjustly assumed that for instance T6 to T8 fall within the 800 ka window. Because the spacing between subsequent terrace levels and the timing of formation is unequal, incorrect uplift rates would be generated. But, as terrace formation is insensitive to differential changes in uplift and only total uplift matters, this would still generate the same amount of terraces, albeit at a slightly different altitude. It would certainly explain why at step 1053 between 20 and 40 m, there is consistently one terrace too much in all scenarios. For instance, in scenarios 1a and 1b, there is one level too much around 38 m. Butzer (1967) already noticed that there was a great variation in height for T4. He found values ranging from 36 m to 44 m. In this thesis a relatively high standard deviation for the T4 terrace height (see Table 1) was found. And the same goes for T5. The model consistently simulates one level too much between roughly 45 and 60 m. Instead of linking this terrace to T5 or T6, perhaps an extra level is present. Butzer (1967) found T5 varying from 50 m to 59 m and in my research T5 has a very high standard deviation of 2.5 m in Galicia. Unfortunately, without knowledge of absolute ages for at least a number of terraces, this idea cannot further be explored.

10.4 Limitations of a 2D model

Only in the Bierzo and in the lower Miño sedimentation takes place, even though alluvial terraces are present in the entire catchment. This suggests that other factors than the ones incorporated in the model are key in terrace formation and preservation. A look on a random geological map of the area reveals that all areas with terraces in the Sil and Miño are situated either in small basins or in areas of high rock fracturation. In both cases a spatial factor could be the main player. After all, basins capture sediments from the surrounding areas, thus ensuring a continuous supply of sediments. They also enhance sedimentation by the river itself. The river's water volume can be spread out over a larger surface thus promoting a decrease in carrying capacity and hence, deposition of sediments. In the case of rock fracturation, total rock mass is weaker. A rapid flowing stream such as the Miño or Sil could therefore easily erode the weakened rock and create a basin-like structure. That in turn would favour deposition and fluvial terrace formation. As Fluver 2 cannot simulate basin structures, these terraces cannot be formed. It is therefore advisable to incorporate Fluver 2 into a 3D modelling body in order to facilitate terrace formation research in a 3D computing environment.

10.5 Age control

Age control remains the weak point of this modelling exercise. There were previously no terrace ages available, so there was no set time-window to operate in. The OSL-dating experiments carried out for this research showed that the OSL signal was near at or reached saturation for all older samples. The only thing we can therefore say is that the T6 and T7 terraces are at least 100 to 200 ka old. The exact boundary is under discussion at the moment of writing. Still, the modelling results for the lower Miño strongly point in the direction of a dominant 100 ka cyclicity for each fluvial terrace with terrace aggradation starting at interglacials. One could argue that this timing is an artefact of the model input. After all, we constructed a number of uplift scenarios in which each terrace was either linked to an interglacial or a glacial, with a total of 8 or 9 terraces. This automatically generated a modelling time span of around 800 ka. In this way the road was paved for the spawning of a 100 ka cyclicity in the system, or not? This remark is affirmed and rejected at the same time. Yes, the model assumptions lead to a time window of 800 ka that facilitates a dominant 100 ka pattern. I say facilitate, because it did not have to be like that. After all, an uplift scenario was included that linked terrace formation to glacial periods. But this scenario still yielded terrace aggradation during interglacials. Then again, this does not mean anything. The only thing a random uplift scenario did was set the total amount of uplift and divide the total amount of uplift over a number of time intervals as depicted in Figure 6. An uplift scenario did not automatically set terrace aggradation at glacials or interglacials at all. Even better, the modelling results suggest that more terrace levels are present than previously expected and thus the reconstructed uplift rates and assumed terraces ages could be wrong for the first half of the modelling exercise. Nonetheless, all model runs still show terrace formation on a 100 ka frequency base, starting at interglacial high sea stands. Cutting the modelling period in for instance half will not solve anything. the PEMs and terrace height reconstructions show without exception that 8 terrace levels at a realistic altitude will not form in a shorter time period. Even though terrace formation occurs during minor high sea stand, this is still not enough to simulate the terraces found in the field. This proves that eustatic control on a 100 ka basis is a very dominant factor in terrace formation and simply means that we most likely have made the correct assumption by linking terrace aggradation to interglacials. It should be noted that in many other river systems, fill terraces are formed under glacial conditions, even close to the coast and on the temporarily exposed continental shelf (see Bridgland et al. 2004), but this is mostly valid for systems with a very large continental shelf, such as North Sea basin in NW Europe. Bridgland et al. (2004) argue that “the forcing of river terrace formation by sea level changes…appears to be of negligible importance, influential only close to the coast, and most effective…where the continental shelf is narrow (Schumm, 1993)”. This is exactly the case for the Miño-Sil system, where the shelf is only ~40 km wide.

It is not possible to reconstruct how fast the sedimentary wedge moves upstream and how long eustacy dominates the upstream part of the Miño-Sil. Neither is it possible to say something about time control on complex response behaviour between different reaches of the system. Placing complex response behaviour within a climate-forced framework as done by Veldkamp & Tebbens (2001) is not feasible for this research. A 100 ka frequency control is the most detailed time-span observable. It has been discussed at length that the unrealistic submarine profile possibly is a hindrance to a correct timing of these events. These processes should therefore not be quantified with respect to time. We can only say that certain processes take place along certain river reaches without specifying their exact duration.

10.6 Placing the Miño terraces in larger perspective

The proposed uplift rates fall within the range of uplift reconstructed for most NW European river basins. The Thames in England has been uplifting with a rate of 0.07 m/ka (Maddy, 1997); The British Avon experienced uplift rates of 0.08-0.09 m/ka for the past 0.7 Ma (Westaway et al., 2006); during the past 0.8 Ma uplift rates for the French Allier/Loire system were around 0.08-0.2 m/ka (Veldkamp & Van Dijke, 1998 and references therein); The Dutch Meuse system registered uplift rates of 0.9 m/ka for the past 0.9 Ma around Maastricht (Van den Berg, 1996); and uplift for the French Seine at Rouen was estimated at 0.12-0.08 m/ka (Westaway, 2002); For more examples see Westaway (2002).
Uplift rates for the Galician Miño were estimated between 0.09 m/ka (scenario 4) and 0.10 m/ka (scenario 1). These rates perfectly match the uplift rates of the NW European rivers. Moreover, around 0.5 Ma, crustal uplift slows down in the Miño. This is clearly seen in Figure 6, where the uplift curve for scenario 2 becomes less steep around 0.5 Ma. Westaway's work (Westaway 2002; Westaway et al., 2006) shows that for all NW European river basins, crustal uplift decreases around 0.5 Ma. Of course, Westaway applies his model of lower crustal flow to all the river basins he investigates. The outcome will therefore most likely always give the same decrease in uplift around 0.5 Ma. Nonetheless, these observations suggest that crustal uplift in NW Iberia is governed by the same factors that drive uplift elsewhere in NW Europe. It has been observed that the Quaternary globally experiences an increase in uplift (see e.g. Van den Berg, 1996; Westaway, 2002; Veldkamp et al., 2007). The driving mechanisms are still under debate. Possible explanations include crustal thickening due to flow in the lower crust (Westaway, 2002), intra-plate stress (Cloetingh et al., 2005), or denudation isostacy (Bishop, 2007).

Chapter 11 Conclusions and recommendations

11.1 Conclusions

In the lower Miño at present at least 10 fluvial terrace levels are found up to 95 m above sea level. Aggradation of these terraces takes place during interglacials when sea level is high, and incision during glacials when sea level is low. Eight main cycles of deposition and incision were simulated, which are interpreted as alluvial terraces. This is the same amount of terraces as assumed in scenario 2. It confirms the eustatic control in the 100 ka frequency band (eccentricity) on terrace formation in the lower Miño and shows that during the Holocene, terrace aggradation is still ongoing. The height of the simulated terraces only partly agrees with field evidence. This disparity is attributed to 2 causes: 1. the assumed gradient of the Miño profile on the continental shelf is too steep thereby causing too much incision close to the land-sea transition; and 2. there could be more fluvial terraces present than previously assumed.
The fluvial terraces are formed in the context of a backfilling sedimentary wedge that starts at the Atlantic Ocean and moves upstream to approximately 280 km along the profile. This is in reasonable agreement with field evidence as the sedimentary wedge is found at least up to 300 km, and possibly further upstream. Modelling results indicate that the sedimentary wedge also migrates through time and takes up over 100 ka to reach the point farthest inland. It is not clear whether this time-span is real or an artefact of an incorrectly modelled Miño river profile on the continental shelf.
Base-level changes continue to exert their influence upstream of the sedimentary wedge in the form of incision processes. The time-lag of base-level control on the upstream reaches is considerable, causing the downstream and upstream reaches to be out of phase.

Apart from eustacy, sediment supply is the other main driver of terrace formation, with modelled increased sediment loads during interglacials and decreased loads during glacials. These sediment loads are in turn controlled by increases and decreases in discharge. Especially in the upper and middle reaches of the Miño-Sil system, are climate controlled erosion processes in the 100 ka frequency band the key factor in profile development. Due to the absence of overland flow and slope processes during glacials as model input, the climate-controlled erosion and deposition processes are considered too linear. A more complex sediment distribution through time is therefore expected as suggested by Van den Berg (1996) and Tebbens et al. (2000). Eustatic control on the other hand, diminishes in the middle and upper reaches, albeit its influence is felt far upstream.
Terrace formation is furthermore controlled by uplift in the Miño-Sil catchment. Field work has demonstrated that there is no difference in uplift between the Galician and Portuguese side of the lower Miño, as on both sides of the river the same amount of terraces on the same height is found. The importance of uplift in the area has been demonstrated by a number of arguments:

1. Model runs without an uplift component as demonstrated for scenario 0 yield an unstable modelled longitudinal profile and generate terrace levels below the current Miño water table. Also, the height differences between these terraces do not agree with field evidence.
2. On the contrary, scenarios that incorporate an uplift component calculated from terrace heights yield the correct amount of terraces at heights that approximate the terraces found in the field.
3. The derived uplift rates agree with those from all major rivers in the Northeast Atlantic region, thus confirming the global trend in uplift during the Quaternary.

11.2 Recommendations for further research

Subsequent research should focus on the following themes:

1. Improve the input for the currently submerged part of the Miño profile. First of all, a more realistic input of the initial profile is needed. This can be achieved by studying borehole and seismic data. Then, improved modelling of coastal delta processes is needed, preferably in a lateral (3D) way.
2. Dating of the fluvial terraces with techniques that allow dating of older sediments, for instance with K-Ar, U/Th, Be^{10} or other dating techniques.
3. A renewed investigation of the fluvial terraces in the lower Miño to find missing terrace levels. Mapping of the terraces is preferred above single observations. Additionally, the link between the fluvial and marine environment must be established, for instance through mapping of marine terraces and fluvial terraces close to the Miño outlet.
4. Construct a 3D version of Fluver to accommodate a spatial dimension. In this way a more improved hill slope sediment supply, basin-like structures and more realistic spatially and temporarily variable erosion resistance rates can be taken into account. That would facilitate the simulation of the fluvial terraces in the Bierzo and its satellite basins.
5. Perform new simulations with a more advanced input for discharge and sediment supply. A more detailed DEM will be needed to facilitate more precise reconstruction of terrace positions and heights and river profile development in general.
6. Investigation of paleosol formation in the older terraces. This is useful for reconstructing the past sedimentary environments and prevailing climates.

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Appendix 1a Terrace inventory sheet

Terrace location			
Day of fieldwork			
Date			
Time			
Measurement number			
Terrace number on transect			
Type of landuse			
Amount of photo's taken			
E terrace surface			
N terrace surface			
Height terrace surface above scarp field measurement			
Height above scarp digi map/gps			
E terrace base			
N terrace base			
Height terrace base field meas.			
Height terrace base digi map/gps			
E max. height terrace surface			
N max. height terrace surface			
Maximum height terrace where terrace ends (if applicable)			
Max. height surface digi map/gps			
Remarks			
Terrace location			
Day of fieldwork			
Date			
Time			
Measurement number			
Terrace number on transect			
Type of landuse			
Amount of photo's taken			
E terrace surface			
N terrace surface			
Height terrace surface above scarp field measurement			
Height above scarp digi map/gps			
E terrace base			
N terrace base			
Height terrace base field meas.			
Height terrace base digi map/gps			
E max. height terrace surface			
N max. height terrace surface			
Maximum height terrace where terrace ends (if applicable)			
Max. height surface digi map/gps			
Remarks			

Appendix 1b Enclosure sheet

Enclosure		**Drawing**
Day of fieldwork		
Date		
Time		
Measurement number		
Terrace number on transect		
Type of landuse		
GPS E		
GPS N		
Height base enclosure field m		
Height top enclosure field m		
Height base digital map/gps m		
Heigt top digital map/gps m		
Amount of sediment visible m		
Presence of paleostructures		
Paleosols y/n		
Sample taken y/n		
Photo taken y/n		

Layer #	From - to	Gravel size	Gravel composition %	Gravel sorting	Rounded etc	Matrix size	Matrix comp.	Matrix color	Matrix sorting	Carbon.	Remarks
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											

Appendix 2 Field data

General							**Terrace surface**					**Terrace base**				
#	**Day**	**Date**	**Time**	**Village or region**	**Terrace #**	**Landuse**	**Easting**	**Northing**	**Height tmap**	**Height digital**	**Corrected height**	**Easting**	**Northing**	**Height tmap**	**Height digital**	**Corrected height**
Galicia																
1	1	15-4-2007	14:00	Salvaterra	T6	forest	541000	4659789	69	65		540963	4659596	50	45	
2	1	15-4-2007	14:30	Salvaterra	T7	industrial	541122	4660046	78	75		541110	4659973	69	65	
3	1	15-4-2007	17:00	Salvaterra	T4	village	541387	4659585	40	40		540669	4658986	31	32	
5	1	15-4-2007	17:38	Porto	T0	woodland	538400	4656658	12	7		***	***	***	***	
6	1	15-4-2007	17:52	Porto	T1	vineyard	538408	4656674	17	14		538400	4656658	12	7	
9	1	15-4-2007	18:30	Porto	T3	vineyard	538614	4656824	40	31		538422	4656814	20	15	
15	2	16-4-2007	14:54	Caldelas	T5	woodland	535976	4656781	53	50		535896	4656678	42	37	
16	2	16-4-2007	17:27	Caldelas	T7	forest	536229	4656980	80	75		536123	4656906	65	55	
18	3	17-4-2007	11:15	Guillarei	(T0)	beach	531462	4656062	3	7		***	***	***	***	
19	3	17-4-2007	11:20	Guillarei	T0	pasture	531462	4656080	7	8		***	***	***	***	
21	3	17-4-2007	14:25	Guillarei	T4	pasture	531381	4657678	35	40		531381	4657750	?	36	
24	3	17-4-2007	20:15	Guillarei	bedrock	village	532500	4657250	30	35		***	***	***	***	
25	3	17-4-2007	21:30	Guillarei	T5	forest	533141	4657668	55	55		?	?	45	?	
26	4	18-4-2007	12:00	Soutelo	colluvium	pasture	533500	4658500	70	70		***	***	***	***	
27	4	18-4-2007	15:10	Guillarei	T7	forest	530500	4658060	70	73		530579	4658019	60	50	
28	4	18-4-2007	17:12	Sobrada	T0	vineyard	528249	4651604	5	7		***	***	***	***	
29	4	18-4-2007	17:15	Sobrada	T2	forest	528074	4651703	20	24		528249	4651604	5	5	
30	4	18-4-2007	17:34	Sobrada	T3	vineyard	527958	4651722	31	36		528030	4651705	20	27	
31	4	18-4-2007	17:50	Sobrada	T4	vineyard	527741	4651700	38	40		527958	4651722	31	36	
32	4	18-4-2007	18:00	Sobrada	T5	village	527522	4651815	45	55		527741	4651700	38	40	
33	4	18-4-2007	18:09	Sobrada	?	village	527404	4651603	45	48		?	?	?	?	
34	4	18-4-2007	18:30	Sobrada	?	village	527175	4651732	52	57		527266	4651686	48	52	
35	4	18-4-2007	18:44	Sobrada	T7	forest	526703	4651743	70	75		526950	4651760	57	63	
36	5	19-4-2007	12:46	Amorin	T0	vineyard	523922	4648133	5	6		***	***	***	***	
37	5	19-4-2007	13:05	Amorin	(T0)	vineyard	523922	4648372	10	8		***	***	***	***	
38	5	19-4-2007	14:40	Amorin	T1	village	524200	4649227	20	17		524184	4649144	14	15	
39	5	19-4-2007	14:45	Amorin	T2	forest	524028	4649478	24	27		524200	4649227	20	17	
40	5	19-4-2007	15:03	Amorin	T4	forest	524020	4649679	44	39		524028	4649498	24	27	
41	5	19-4-2007	15:21	Amorin	T5	forest	524206	4650166	52	55		524095	4650073	48	49	
42	5	19-4-2007	17:20	Amorin	T6	village	523450	4650500	68	66		523496	4650210	50	48	

	Maximum altitude of terrace surface					General
#	Easting	Northing	Height tmap	Max digital	Corrected height	Remarks
1						
2	541318	4660619	87	85		
3			50			
5						
6			20			Measurements 5 and 6 possibly one terrace instead of two.
9						Terrace on top of bedrock, thin veneer of gravel.
15						According to geomap not a terrace, but in field very clear steep scarp, also on aerial photograph.
16	536229	4657100	82	75		
18						Day 3 very bad day. Levels between 9-40 m not clear.
19	531719	4656700	10	10		
21	531619	4657737	40	41		Terrace very flat and large at top. Very clearly a terrace, no doubt! Base not visible.
24						Terrace ends, bedrock slope takes over.
25	533150	4657960	62	55		Terrace ends, no higher scarp but smooth transition to bedrock. Thick pile of sediment at 55 m.
26						Day 4 in general good day; clear terraces. Nr. 26 is not a terrace!
27			70			Highest terrace. Excellent for sampling.
28						Very clear terrace.
29						Very clear terrace, probably glacis.
30						Very big and flat terrce, very clear.
31						Guess. Terrace transition not clear.
32						Guess.
33						Clear terrace with terrace scarp and flat surface.
34						Clear terrace scarp, flat at top.
35						Terrace with gentle slope but flat at the top with sediment.
36						Day 5 bad day.
37						
38						Very gentle slope, but noticable.
39						Not sure if terraces end here or continues to 44 m.
40						Definately terrace, steep slope, relatively flat and lots of sediment.
41						Clearly a terrace, steep slope.
42						Clear scarp face (partly excavated), lots of sediment.

General							Terrace surface					Terrace base				
#	Day	Date	Time	Village or region	Terrace #	Landuse	Easting	Northing	Height tmap	Height digital	Corrected height	Easting	Northing	Height tmap	Height digital	Corrected height
Galicia																
43	5	19-4-2007	16:36	Amorin	bedrock	village	523877	4651293	79	79		***	***	***	***	
45	6	20-4-2007	13:36	Tomiño	T0	pasture	522792	4647603	5	6		***	***	***	***	
46	6	20-4-2007	14:47	Tomiño	(T0)	pasture	522538	4647938	10	10		***	***	***	***	
47	6	20-4-2007	15:15	Tomiño	T1	pasture	522269	4648064	20	15		522236	4647960	18	19	
48	6	20-4-2007	15:38	Tomiño	T4	pasture	522069	4648344	35	35		522171	4648152	28	23	
49	6	20-4-2007	16:00	Tomiño	T5	forest	521800	4648500	50	50		521952	4648311	40	35	
50	6	20-4-2007	17:01	Tomiño	bedrock	forest	521375	4649550	69	68		521800	4648500	55	46	
51	7	26-4-2007	16:48	Estas	T2	village	520143	4647189	28	25		520350	4647039	18	10	
52	7	26-4-2007	18:05	Os Bravos	(T0)	forest	520672	4645906	2	7		***	***	***	***	
53	7	26-4-2007	18:06	Os Bravos	T0	pasture	520636	4645912	4	8		***	***	***	***	
54	7	26-4-2007	20:07	Os Bravos	T3	village	519414	4646628	30	28		519414	4646608	28	27	
55	7	26-4-2007	20:45	Os Bravos	T3	village	519414	4646608	28	27		519466	4646555	21	22	
56	7	26-4-2007	20:59	Os Bravos	T5	village	519204	4646837	42	49		519414	464618	31	31	
57	8	27-4-2007	12:10	Figueiro	(T0)	forest	520700	4645500	2	7		***	***	***	***	
58	8	27-4-2007	12:21	Figueiro	T0	orchard	520552	4645477	4	8		***	***	***	***	
59	8	27-4-2007	15:51	Figueiro	T2	village	519175	4645930	20	23		519950	4645780	9	7	
60	8	27-4-2007	16:30	Figueiro	T3	village	518974	4645947	25	27		519175	4645477	18	16	
61	8	27-4-2007	18:59	Figueiro	T4	village	518675	4646097	42	40		518823	4645966	30	36	
62	8	27-4-2007	18:23	Figueiro	T5	village	518591	4646330	52	52		518596	4646150	42	42	
63	8	27-4-2007	18:30	Figueiro	bedrock	forest	518330	4646375	60	64		***	***	***	***	
65	9	28-4-2007	17:30	Estas	(T0)	pasture	520981	4646306	2	7		***	***	***	***	
66	9	28-4-2007	17:40	Estas	T0	pasture	520904	4646401	4	7		***	***	***	***	
67	9	28-4-2007	18:00	Estas	T1	vineyard	520250	4647075	18	15		520450	4646820	9	9	
68	9	28-4-2007	19:21	Estas	T4	village	519940	4647548	41	42		519936	4647476	29	30	
69	9	28-4-2007	20:33	Estas	T5	forest	519873	4647589	54	50		519940	4647548	41	42	
71	10	29-4-2007	16:30	Goian	colluvium	forest	520576	4643542	20	20		***	***	***	***	
73	10	29-4-2007	17:10	Goian	T0	grassland	520835	4644139	5	4		***	***	***	***	
74	10	29-4-2007	18:10	Goian	T2	grassland	520575	4643851	19	22		?	?	?	?	
75	10	29-4-2007	18:56	Goian	T4	forest	520154	4643840	32	42		520267	4643804	32	32	
76	10	29-4-2007	20:10	Goian	T3	pasture	520416	4643659	27	32		520575	4643851	19	22	
77	10	29-4-2007	20:55	Goian	?	village	518517	4644016	32	37		?	?	?	?	
78	10	29-4-2007	21:40	Goian	(T4)	village	517912	4644179	42	45		518517	4644016	32	37	
79	11	30-4-2007	12:03	Goian	(T4)	village	518250	4644394	43	47		518588	4644253	33	30	
80	11	30-4-2007	14:44	Goian	T4	vineyard	517629	4643235	40	42		517826	4643319	30	30	

	Maximum altitude of terrace surface					General
#	Easting	Northing	Height tmap	Max digital	Corrected height	Remarks
43						
45						Day 6 bad day
46						GPS not working very well.
47						
48						Very unclear terrace, not very flat.
49			55			Very steep scarp face, flat with sediment.
50						Could have been terrace, few pebbles present. According to notes 55 m max height terrace...!
51						Extremely well preserved terrace.
52						Definately T0, but colluvium obscured transition T0-T1. 4 m measurement therefore not sure.
53						Very big and flat terrace.
54						Colluvium between 4-21 m. Scarp faces not visible anymore; terraces transitions unclear.
55						Perhaps measured a bit too much direction river, but definately terrace.
56						Clear scarp face, flat and sediment.
57						Took coordinates from map. Could not reach Miño.
58	520700	4645500	9	4		Very flat, big.
59						Good measurement.
60			30			
61						Good measurement.
62			52			Good measurement.
63						
65						Day 9 excellent day with clearly visible terraces.
66						Large and flat terrace.
67						Base terrace could not be found because of colluvium. Used geological map to locate base, surface.
68						Slope excavated, but big height difference indicates start of new terrace.
69						Good sampling site, lots of sediment.
71						Colluvium from beach up to this measurement.
73						Good measurement, max. height could not be found because of brook forest.
74						Good measurement, flat terrace close to church.
75						This is a correct but strange measurement and not representative for the general level (see 1:5000).
76			32			Steep slope, very flat at the top.
77						Good measurement. Very flat, lots of sediment and an enclosure.
78			45			Gently sloping terrace, scarp not visible, but a lot of sediment. Good measurement.
79	517747	4644627	45	45		Very steep slope, flat at top, clear indications of gravel. Very good measurement.
80						Good measurement with enclosure. Sample taken.

General							Terrace surface					Terrace base				
#	Day	Date	Time	Village or region	Terrace #	Landuse	Easting	Northing	Height tmap	Height digital	Corrected height	Easting	Northing	Height tmap	Height digital	Corrected height
Galicia																
81	12	1-5-2007	11:47	Tabagon	T0	grassland	516700	4641000	3	4		***	***	***	***	
82	12	1-5-2007	12:14	Tabagon	colluvium	village	516666	4642056	20	20		***	***	***	***	
83	12	1-5-2007	15:00	Salcidos	T0	wetland	513264	4640049	8	5		***	***	***	***	
84	11	30-4-2007	18:59	Goian	?	village	519067	4643466	32	38		519096	4643302	19	20	
85	11	30-4-2007	19:17	Goian	T1	village	519096	4643302	19	15		519110	4643180	9	12	
86	12	1-5-2007	15:05	Salcidos	T0	grassland	513226	4640160	10	6		***	***	***	***	
87	12	1-5-2007	15:40	Salcidos	T1	village	513240	4640353	16	13		513226	4640160	10	6	
88	12	1-5-2007	16:46	Salcidos	T4	vineyard	513323	4641615	40	42		513367	4641339	30	30	
89	12	1-5-2007	18:13	Salcidos	T5	village	512875	4641600	50	50		513172	4641482	42	38	
90	13	2-5-2007	12:44	A Pasaxe	T0	wetland	512592	4638430	7	5		***	***	***	***	
91	13	2-5-2007	12:50	A Pasaxe	T1	grassland	512582	4638451	9	8		512592	4638430	7	5	
93	13	2-5-2007	17:30	Caldelas	T0	grassland	535696	4656042	8	7		***	***	***	***	
94	13	2-5-2007	17:32	Caldelas	T1	grassland	535696	4656060	11	14		535696	4656042	8	7	
95	13	2-5-2007	17:50	Caldelas	T2	village	535393	4656479	26	24		535772	4656230	18	15	
96	13	2-5-2007	18:32	Caldelas	T3	village	535419	4656580	32	31		535270	4656596	28	27	
97	13	2-5-2007	18:43	Caldelas	T4	village	535327	4656830	50	42		535270	4656596	28	27	
98	13	2-5-2007	19:13	Caldelas	T6	village	535500	4657064	60	65		535327	4656830	50	42	
99	13	2-5-2007	21:42	Caldelas	T7	forest	536242	4657159	80	75		536082	4656940	64	54	
100	14	3-5-2007	15:40	Salvaterra	T0	grassland	540783	4658828	10	8		***	***	***	***	
101	14	3-5-2007	15:50	Salvaterra	T1	vineyard	540555	4658876	14	15		540783	4658828	10	8	
102	14	3-5-2007	16:22	Salvaterra	T3	forest	540672	4659144	31	32		540669	4658986	20	17	
103	15	4-5-2007	16:08	Oleiros	T0	beach	544556	4659231	10	9		***	***	***	***	
104	15	4-5-2007	16:17	Oleiros	T1	forest	544988	4659307	14	15		544556	4659231	10	9	
105	15	4-5-2007	16:28	Oleiros	T4	gravelpit	545275	4660434	40	41		545010	4659362	18	21	
106	15	4-5-2007	20:47	Oleiros	T6	woodland	545800	4660700	57	65		545600	4660531	47	46	
107	15	4-5-2007	20:57	Oleiros	bedrock	forest	545983	4661332	90	90		545720	4660946	66	66	
108	16	5-5-2007	14:01	Vide	T0	beach	550563	4658629	12	11		***	***	***	***	
109	16	5-5-2007	14:06	Vide	T3	grassland	550610	4658837	20	32		550563	4658629	12	11	
110	16	5-5-2007	14:30	Vide	T4	forest	550665	4658861	40	40		550610	4658861	20	32	
111	16	5-5-2007	15:34	Vide	T6	forest	551147	4659183	60	69		551005	4659020	40	50	
113	16	5-5-2007	16:56	Vide	T7	gravelpit	550733	4659520	76	76		550776	4659388	62	68	
114	16	5-5-2007	18:00	Oleiros	T4	gravelpit	545917	4660543	45	45		545010	4659362	18	21	

	Maximum altitude of terrace surface					General
#	Easting	Northing	Height tmap	Max digital	Corrected height	Remarks
81	516875	4641750	10	12		Transition T0-terrace not visible. Very altered landscape and very flat.
82						No terrace sediment visible although area is very flat. Could be eroded.
83						Day 12 very bad day. Terraces could not be recognised because of erosion and proximity to the sea.
84						
85						Not sure about this measurement.
86						No scarp face visible. Relied on geological map and aerials.
87						
88						Flat area with sediments.
89			52			Very unclear terrace without scarp face. Indicated by geological map.
90	512501	4638560	7	8		Good measurement.
91						Very good measurement. Old fortress at edge of terrace scarp confirms scarp face.
93						Perfect measurement. T0 clearly visible.
94			19			Perfect measurement with perfect terrace.
95						
96			40			Good measurement.
97						
98	535547	4657260	64	65		Flat at the top, sediment present.
99			82			Quite good measurement, immense amount of sediment; good enclosure.
100						
101			20			
102			?			
103						
104						
105			47			
106			66			
107						Sediment present, but no indication of fluvial gravels.
108						Overbank deposits and backswamp.
109						Good measurement. Clear scarp face, flat at the top.
110						Perfect measurement with a 20 m high terrace scarp.
111			69			Good measurement.
113	550936	4659936	86	87		
114						

General							Terrace surface					Terrace base				
#	Day	Date	Time	Village or region	Terrace #	Landuse	Easting	Northing	Height tmap	Height digital	Corrected height	Easting	Northing	Height tmap	Height digital	Corrected height
Portugal																
115	17	6-6-2007	15:33	Barbeita	T0	grassland	549185	4658855	10	9	9	549172	4658873	***	***	***
116	17	6-6-2007	15:45	Barbeita	T3	forest	549155	4658778	31	33	32	549185	4658855	10	9	9
117	17	6-6-2007	16:18	Barbeita	T2	vineyard	549265	4658910	22	24	24	549185	4658855	10	9	9
118	17	6-6-2007	16:42	Barbeita	T4	forest	549434	4658687	42	46	42	549155	4658778	31	33	32
119	17	6-6-2007	17:08	Barbeita	T5	village	549514	4658526	55	60	55	549434	4658687	42	46	42
120	17	6-6-2007	17:50	Barbeita	T6	village	549606	4658302	66	74	66	549514	4658526	55	60	55
121	17	6-6-2007	18:25	Barbeita	T7	forest	549568	4658104	82	80	80	549606	4658302	66	74	66
122	17	6-6-2007	19:53	Bela	bedrock	forest	547993	4658217	25	25	25	***	***	***	***	***
123	17	6-6-2007	20:14	Bela	T3	forest	547994	4658107	31	37	31	?	?	?	?	?
124	17	6-6-2007	20:47	Bela	T4	forest	548031	4657915	39	40	40	547994	4658107	31	37	31
125	17	6-6-2007	21:01	Bela	T6	forest	548411	4657506	69	75	69	548031	4657915	39	40	40
126	17	6-6-2007	21:45	Bela	bedrock	village	548506	4657179	88	94	88	548411	4657506	69	75	
127	18	7-6-2007	10:59	Troviscoso	T7	forest	546800	4657442	75	77	76	546690	4657636	68	68	68
128	18	7-6-2007	11:49	Troviscoso	T0	beach	545288	4659174	9	9	9	***	***	***	***	***
129	18	7-6-2007	12:06	Troviscoso	(T1)	grassland	545289	4659145	13	12	13	545288	4659174	9	9	9
130	18	7-6-2007	12:13	Troviscoso	T1	vineyard	545294	4659080	17	16	17	545289	4659145	13	12	13
131	18	7-6-2007	12:31	Troviscoso	T4	village	545550	4658825	43	42	43	545852	4659048	32	41	32
132	18	7-6-2007	13:03	Troviscoso	T3	forest	545852	4659048	32	41	32	545635	4659140	20	22	20
133	18	7-6-2007	14:20	Troviscoso	T6	village	545752	4658035	65	63	65	544257	4658499	54	51	53
134	18	7-6-2007	14:44	Troviscoso	T7	village	545735	4657699	75	79	75	545752	4658035	65	63	65
135	18	7-6-2007	15:34	Troviscoso	T5	village	544257	4658499	54	51	53	544288	4658664	39	39	39
136	18	7-6-2007	15:43	Troviscoso	T6	forest	544184	4658292	67	67	67	544257	4658499	54	51	53
137	18	7-6-2007	20:54	Monção	T6	forest	542228	4657899	66	68	67	542174	4658197	53	53	53
138	18	7-6-2007	21:09	Monção	T7	vineyard	542132	4657521	78	80	78	542228	4657899	66	68	67
139	19	8-6-2007	11:19	Monção	T0	grassland	542555	4659143	8	8	8	***	***	***	***	***
140	19	8-6-2007	11:25	Monção	T1	vineyard	542530	4659037	12	12	12	542555	4659143	8	8	8
141	19	8-6-2007	12:06	Monção	T4	village	542315	4658646	39	39	39	542390	4658870	18	20	19
142	19	8-6-2007	12:42	Monção	T5	pasture	542129	4658380	49	53	53	542315	4658646	39	39	39
143	19	8-6-2007	17:17	Troporiz	T1	vineyard	538116	4656188	12	13	13	538235	4656337	8	8	8
144	19	8-6-2007	17:28	Troporiz	T0	grassland	538235	4656337	8	8	8	***	***	***	***	***
145	19	8-6-2007	18:04	Troporiz	bedrock	village	538671	4656114	48	46	47	?	?	?	?	?
146	19	8-6-2007	18:16	Troporiz	T7	heather	538821	4655888	78	79	78	?	?	?	?	?

	Maximum altitude of terrace surface					General
#	Easting	Northing	Height tmap	Max digital	Corrected height	Remarks
115						Day 17 measurements 122-126: only 125 proven terrace. Agrees with geological map.
116						Steep scarp almost vertical. flat, thin veneer of sediment. Good measurement.
117						Could be anthropogenic terrace
118						Clear terrace; flat with 1 m of sediment on top. Field measurement height perhaps better than GPS.
119						Clear terrace, flat and sediment. Good measurement although GPS remains on 60 m.
120						Clear terrace, flat but not a steep scarp. Field measurement is correct, GPS measurement not.
121						Clear terrace with sediment. Flat, steep scarp. GPS measurement is correct.
122						Steep canyon, no floodplain or other terrace.
123						GPS not functioning well in forest. Field measurement is accurate. Pebbles, but more like colluvium.
124						Every now and then a stray pebble; cemented clay/sandy material which resembles colluvium.
125						Clear terrace, steep scarp. Plenty of colluvium but also big rounded gravels. Good measurement.
126						Flat and a scarp but no sediments. Probably a former terrace.
127						Good measurement. Happened to drive past. Flat and a lot of sediment.
128						Cobbles beach up to 40 cm. High energetic environment.
129						Probably part of T0, scarp is severely eroded.
130						Clear terrace, scarp, flat and very sandy, few cobbles. Good measurement.
131						Extremely clear terrace. Scarp face of at least 20 m. Flat at top, sediments.
132						Field msuremnt 29 m good one (up to 32 m level). GPS not working in forest. Clear terrace.
133						Reasonable measurement.
134						Good measurement. Flat, scarp and a lot of sediment.
135						At soccer field. Sediment, flat and scarp face. Good measurement.
136						Good measurement right at the terrace surface. Lots of sediment, steep scarp and flat.
137						Good measurement. Flat and a lot of sediment.
138	542202	4657266	87	87	87	Good measurement. Flat, scarp and a lot of sediment.
139						Day 19 Monção good measurements.
140	542390	4658870	18	20	19	Steep scarp face with road on top of terrace surface.
141						Clear scarp face, very steep. Flat terrace surface and lot of sediment. Good measurement.
142						Good measurement.
143			19			Day 19 reasonable measurements given what the aerials and geological map predicted.
144						
145						Not a good measurement. If not correct use base nr 147. Contained little gravel.
146			80	81	80	Flat and sediment. Good meas. Base partly excavated; transition from former terrace not visible.

General							Terrace surface					Terrace base				
#	Day	Date	Time	Village or region	Terrace #	Landuse	Easting	Northing	Height tmap	Height digital	Corrected height	Easting	Northing	Height tmap	Height digital	Corrected height
Portugal																
147	19	8-6-2007	18:52	Troporiz	T6	heather	538993	4656277	65	65	65	538885	4656398	50	49	50
148	19	8-6-2007	19:24	Troporiz	T5	forest	538885	4656398	50	49	50	538767	4656436	39	41	40
149	19	8-6-2007	20:56	Troporiz	T9	forest	540140	4655737	96	95	95	539583	4655998	80	81	80
150	20	9-6-2007	13:46	Friestas	T0	beach	536258	4655861	9	7	8	***	***	***	***	***
151	20	9-6-2007	14:10	Friestas	T1	vineyard	536258	4655784	13	12	12	536258	4655861	9	7	8
152	20	9-6-2007	14:30	Friestas	T3	vineyard	535662	4655623	31	32	32	536252	4655666	18	16	18
153	20	9-6-2007	14:50	Friestas	T4	vineyard	536255	4655401	42	40	40	535662	4655623	31	32	32
154	20	9-6-2007	15:01	Friestas	T5	village	536173	4655170	52	53	52	536255	4655401	40	42	40
155	20	9-6-2007	15:20	Friestas	T6	forest	536182	4655007	62	66	66	536183	4655087	56	54	55
156	20	9-6-2007	15:41	Friestas	T7	village	536277	4654804	72	74	73	536182	4655007	62	66	66
157	20	9-6-2007	15:59	Friestas	T8	forest	536384	4654513	84	84	84	536277	4654804	72	74	73
158	21	10-6-2007	12:38	Ganfei	T0	pasture	532005	4655770	9	8	8	***	***	***	***	***
159	21	10-6-2007	12:43	Ganfei	T1	vineyard	531912	4655730	11	14	14	532005	4655770	9	8	8
160	21	10-6-2007	13:06	Ganfei	T2	village	532180	4655495	24	25	25	532152	4655565	19	19	19
161	21	10-6-2007	13:41	Ganfei	T3	vineyard	532257	4655416	32	38	32	532180	4655495	25	25	25
162	21	10-6-2007	14:20	Ganfei	bedrock	village	532260	4655017	52	52	52	***	***	***	***	***
163	21	10-6-2007	14:30	Ganfei	T5	village	532210	4654951	50	52	50	?	?	?	?	?
164	21	10-6-2007	14:56	Ganfei	T3	vineyard	531966	4654949	30	30	30	532180	4655565	24	25	25
165	22	12-6-2007	13:43	Moledo	not Miño	grassland	511720	4632873	41	41	41	511557	4632977	24	24	24
166	22	12-6-2007	14:20	Moledo	not Miño	grassland	512051	4632845	54	53	53	511838	4632844	45	46	45
167	22	12-6-2007	14:46	Moledo	bedrock	village	512353	4632916	54	54	54	***	***	***	***	***
168	22	12-6-2007	16:38	Cristelo	not Miño	village	512752	4633718	42	42	42	512680	4633862	30	?	30
169	22	12-6-2007	20:54	Seixas	T5	village	515315	4637028	52	54	52	515156	4637119	36	37	36
170	22	12-6-2007	21:03	Seixas	T4	forest	515256	4636599	40	41	40	?	?	?	?	?
171	22	12-6-2007	21:50	Seixas	T4	forest	515156	4637119	36	37	36	515060	4637073	20	22	21
172	22	12-6-2007	22:34	Seixas	T0	wetland	516037	4639144	6	6	6	***	***	***	***	***
173	23	13-6-2007	12:07	Seixas	T0	wetland	514660	4637697	6	5	5	***	***	***	***	***
174	23	13-6-2007	12:44	Lanhelas	T5	vineyard	515232	4637450	49	50	50	514942	4637601	34	33	33
175	23	13-6-2007	14:05	Lanhelas	T1	village	516901	4639395	9	9	9	517292	4640135	5	6	6
176	23	13-6-2007	14:29	Lanhelas	T2	village	517000	4639483	24	23	24	516901	4639395	9	9	9
177	23	13-6-2007	15:06	Lanhelas	T3	village	517448	4639720	27	31	30	?	?	?	?	?
178	23	13-6-2007	16:25	Lanhelas	T0	pasture	517292	4640135	5	6	6	***	***	***	***	***

	Maximum altitude of terrace surface					General
#	Easting	Northing	Height tmap	Max digital	Corrected height	Remarks
147						Sediments present but very eroded terrace. Not best terrace for height measurements.
148						Scarp clearly visible although partly excavated. Base easily located, area flattens but without sediment.
149						Coordinates taken on soccer field because of surrounding forest. Very good meas, lots of sediment.
150						Good measurement.
151	536252	4655666	18	16	18	Good measurement.
152						Good measurement.
153						Good measurement.
154						Not sure about this measurement. Unclear where scarp face ends and terrace surface starts.
155						Excellently preserved terrace. Good measurement.
156						Good measurement. Flat, scarp and a lot of sediment.
157						Very clear scarp face and flat surface. Lots of sediments. Good measurement.
158						Transition T0-T1 not clear. Day 21 bad day, terrace surfaces and scarps difficult to locate.
159	532152	4655565	19	19	19	Not a good measurment. Scarp face is 4 m high. So how can difference T0-T1 only be 2 m?
160						Steep scarp, flat at top. Road crosses terrace surface. Further down road big terrace at same height.
161						Steep scarp but terrace surface not flat. Difficult to see where terrace ends. Not very good measurement.
162						Geological map as well indicates bedrock.
163						Base could not be located. Measurement reasonable.
164						Sediment present, reasonably flat. Good/bad measurement? Difficult to judge.
165	511838	4632844	45	46	45	Big and flat surface with gravel. Reasonable measurement.
166						Few pebbles, flat.
167						Steep granite walls.
168						Raining, difficult for GPS to find altitude. Field measurement is OK.
169						At chuch. Terrace material visible.
170						Extremely eroded, bedrock visible but still some pebbles. Flat and scarp face.
171						
172						
173						
174						Sediments, flat and a scarp face. Good measurement, in agreement with Teixeira.
175						Sediments, flat surface. Teixeira indicates 15 m.
176						Sediments present, flat, steep scarp. Clear terrace.
177						Good measurement in agreement with Teixeira.
178						Good measurement in agreement with Teixeira.

General							Terrace surface					Terrace base				
#	Day	Date	Time	Village or region	Terrace #	Landuse	Easting	Northing	Height tmap	Height digital	Corrected height	Easting	Northing	Height tmap	Height digital	Corrected height
Portugal																
179	23	13-6-2007	16:55	Lanhelas	T4	village	517992	4640320	40	39	40	?	?	?	?	?
180	23	13-6-2007	17:43	Seixas	T1	village	515196	4638640	9	15	9	516037	4639144	6	6	6
181	24	14-6-2007	13:44	Gondarem	T0	grassland	518692	4641139	7	7	7	***	***	***	***	***
182	24	14-6-2007	14:00	Gondarem	T1	grassland	518779	4641104	14	13	13	518708	4641124	9	9	9
183	24	14-6-2007	14:16	Gondarem	T3	village	518354	4640991	30	30	30	?	?	?	?	?
184	24	14-6-2007	15:00	Gondarem	T1	grassland	520314	4641372	13	13	13	520227	4641371	9	9	9
185	24	14-6-2007	15:43	Loivo	T0	grassland	520503	4642143	6	6	6	***	***	***	***	***
186	24	14-6-2007	16:26	Loivo	T4	pasture	520816	4641857	40	40	40	?	?	?	?	?
187	25	15-6-2007	11:10	Vila Nova	T0	village	521146	4643459	6	7	7	***	***	***	***	***
188	25	15-6-2007	12:29	Lovelhe	T4	village	521788	4644608	40	39	39	?	?	?	?	?
189	25	15-6-2007	12:54	Lovelhe	T0	grassland	521630	4646058	8	8	8	***	***	***	***	***
190	25	15-6-2007	13:06	Lovelhe	T1	forest	521836	4645937	10	15	15	521744	4645944	8	8	8
191	25	15-6-2007	13:47	Lovelhe	T4	village	522574	4645620	40	40	40	?	?	?	?	?
192	25	15-6-2007	14:02	Lovelhe	T5	village	522598	4645503	53	52	52	522573	4645621	40	40	40
193	25	15-6-2007	14:53	Lovelhe	bedrock	village	522863	4645408	65	69	65	***	***	***	***	***
194	25	15-6-2007	16:26	Reboreda	T0	grassland	524153	4647767	6	7	7	***	***	***	***	***
195	25	15-6-2007	17:14	Reboreda	T1	forest	523882	4647279	15	17	16	524153	4647707	9	9	9
196	25	15-6-2007	18:20	Reboreda	?	village	524170	4646884	37	37	37	524181	4647089	19	19	19
197	25	15-6-2007	19:44	Reboreda	T4	village	524492	4646463	43	44	44	524153	4646814	37	37	37
198	25	15-6-2007	19:50	Reboreda	T5	forest	524425	4646329	54	54	54	524492	4646463	43	44	44
199	25	15-6-2007	20:39	Reboreda	bedrock	forest	524436	4645815	68	71	71	524450	4646053	54	54	54
200	26	16-6-2007	13:43	Vila Meã	T0	grassland	526760	4648865	7	7	7	***	***	***	***	***
201	26	16-6-2007	14:00	Vila Meã	T1	village	526782	4648594	16	16	16	526817	4648730	9	9	9
202	26	16-6-2007	14:20	Vila Meã	T3	forest	527106	4648004	26	30	30	526715	4648533	17	17	17
203	26	16-6-2007	15:40	Vila Meã	T4	forest	527490	4647551	38	36	38	527399	4647645	26	27	26
204	26	16-6-2007	17:16	Vila Meã	T5	forest	527852	4646913	54	54	54	527775	4647103	40	41	40
205	26	16-6-2007	17:51	Vila Meã	T7	heather	527904	4646573	74	77	74	527942	4646750	56	58	57
206	27	28-6-2007	14:28	Cristelo Covo	T0	forest	528601	4652069	8	8	8	***	***	***	***	***
207	27	28-6-2007	14:44	Cristelo Covo	T1	village	528638	4651749	15	20	15	528601	4652069	8	8	8
208	27	28-6-2007	15:14	Cristelo Covo	T2	village	529982	4651796	25	26	25	529226	4651605	19	20	19
209	27	28-6-2007	16:28	Cristelo Covo	T4	village	530373	4651846	34	36	40	529982	4651796	25	26	25
210	27	28-6-2007	17:12	Cristelo Covo	T5	forest	530685	4652183	55	58	56	530437	4652122	39	40	39

	Maximum altitude of terrace surface					General
#	Easting	Northing	Height tmap	Max digital	Corrected height	Remarks
179	518023	4640289	43	43	43	Sediments and flat. Clear terrace and good measurement. In agreement with Teixeira.
180						GPS measurement nog correct because of rain. Church, graveyard and old houses. Teixeira says 15 m.
181						
182						Flat with sediment. Good measurement.
183						Flat and a lot of sediment. Good measurement.
184	520394	4641304	19	13	19	Good measurement.
185						Good measurement.
186						Good measurement. Flat with sediment. Base could not be located.
187						
188						Flat, sediments at church.
189	***					
190	522207	4645850	?	?	?	
191						Flat and sediments.
192						Steep scarp face, flat and sediments. Good measurement.
193						At church. Was probably a terrace (flat) but not sediments left.
194						
195						Good measurement. Big enclosure present suitable for sampling.
196						Not sure about this measurement. Not used in terrace level reconstruction.
197						Reasonable measurment. Not very good, perhaps altitude a bit too high.
198						Good measurement. Scarp face present, flat and a lot of sediment.
199						Scarp face and flat surface but not sediment. Probably eroded terrace.
200	***					Good measurement.
201	526715	4648533	17	17	17	Very clear terrace, flat and steep scarp face with a lot of sediment. Good measurement.
202						Strange terrace. No real scarp but slightly inclinating slope. Transition visible on aerials. 32 m at Vila M.
203			40	40	40	Flat between 36-40 m. Which value to choose?
204						Good measurement. Steep scarp and flat at the top.
205						Terrace nr. 6 not found. No flat surface.
206			19			
207	529226	4651605	19	20	19	Not very good measurement. Scarp unclear. Perhaps 16 m better.
208						Flat, height increasing from T1 onwards. Transition to T3 clear as well: again inclining slope. Sediment.
209			40			Not clear if T3 or T4 or both. Terrace surface inclining slightly in between 30 and 40 m. Scarp and sed.
210						Steep scarp, flat and sediment. Good measurement.

General							Terrace surface					Terrace base				
#	Day	Date	Time	Village or region	Terrace #	Landuse	Easting	Northing	Height tmap	Height digital	Corrected height	Easting	Northing	Height tmap	Height digital	Corrected height
Portugal																
211	27	28-6-2007	17:59	Cristelo Covo	T6	vineyard	531100	4652386	69	71	70	530902	4652390	55	55	55
212	27	28-6-2007	18:08	Cristelo Covo	bedrock	vineyard	531348	4652398	77	77	77	***	***	***	***	***
213	27	28-6-2007	20:05	Portela Conguedo	T0	forest	528500	4650625	7	7	7	***	***	***	***	***
214	27	28-6-2007	20:27	Portela Conguedo	T1	heather	529412	4649903	12	14	13	529125	4650125	9	?	9
215	28	29-6-2007	14:39	Portela Conguedo	T2	village	530196	4650425	24	24	24	529905	4650223	19	20	19
216	28	29-6-2007	15:28	Portela Conguedo	T5	heather	530623	4650316	55	60	55	530413	4650323	31	27	29
217	28	29-6-2007	15:36	Portela Conguedo	T6	heather	530760	4650383	63	66	65	530623	465316	55	60	55
218	28	29-6-2007	17:02	Portela Conguedo	T2	heather	530250	4649750	25	26	25	?	?	?	?	?
219	28	29-6-2007	17:25	Portela Conguedo	T6	heather	530764	4649992	63	64	64	530560	4649990	40	42	41
220	28	29-6-2007	18:36	San Pedro da Torre	T0	village	527354	4649674	7	8	7	***	***	***	***	***
221	28	29-6-2007	18:49	San Pedro da Torre	T1	village	527393	4649586	13	14	14	527373	4649640	10	10	10
222	28	29-6-2007	19:18	San Pedro da Torre	T4	village	528195	4648627	40	41	40	528083	4648800	20	24	22
223	28	29-6-2007	20:05	San Pedro da Torre	T5	forest	528842	4647860	55	54	55	528557	4648161	40	?	40
224	28	29-6-2007	20:57	San Pedro da Torre	T6	village	530633	4646741	67	69	67	530376	4646756	58	60	59
225	28	29-6-2007	21:04	San Pedro da Torre	bedrock	forest	530632	4646902	69	70	70	***	***	***	***	***

	Maximum altitude of terrace surface					General
#	Easting	Northing	Height tmap	Max digital	Corrected height	Remarks
211			72			Steep scarp, flat and a lot of sediment. Clear transition from T5 to T6. Good measurement.
212						Flat, but without sediments.
213			9			Could not reach T0, coordinates and height taken from topomap.
214			19	20	19	Very large terrace surface, a couple of km. Good measurement.
215			29			Transition T1-T2 reasonably clear. Inclining slope but no scarp face as such.
216						Bad measurement. Nor base nor surface clear. Lot of sediment. 40 m level not visible.
217						Flat and a lot of sediment. Very eroded surface. Base not clear, but probably surface #219.
218	530576	4649795	40	?	40	Flat in between 25 and 35 m. Extremely large surface.
219						Good measurement.
220						Good measurement.
221	527786	4649337	21	21	21	Good measurement.
222						Flat and a 20-m high scarp face. Sediment present. Good measurement.
223						Good measurement. Steep 15-m scarp. Flat at top and sediments present.
224			67			Scarp and a bit of sediment. Terrace remnant.
225						

Measurement number.

Village or region Village or area where measurement was taken.

Terrace # Terrace number in sequence. ( ) indicates that the measurement probably has this terrace number but was not used for profile reconstruction.

Height tmap Height in m above MSL of terrace surface or base. Height value taken from 1:25,000 topographical map.

Height digital Height in m above MSL of terrace surface or base as indicated by 1:5000 digital map (Galicia) or GPS (Portugal).

Corrected height Height value used for terrace profile reconstruction. Only applies to the Portugese side as for Galicia the digital heights are used.

*** Value not applicable, for instance when a terrace base could not be found. The T0 never has a base and neither bedrock or colluvium.

? Value could not be found, for instance when only a terrace surface but not the base nor scarp was located.

Appendix 3 Terrace profile data

Galicia

T0			**T1min**			**T1max**			**T2**			**T3**			**T4**		
#	**Place**	**Alt**	**#**	**Place**	**Alt**	**#**	**Place**	**Alt**	**#**	**Place**	**Alt**	**#**	**Place**	**Alt**	**#**	**Place**	**Alt**
108	0.74	11	104	7.86	15	101	12.4	20	95	19.29	24	109	0.67	32	110	0.72	40
103	8.29	9	101	12.4	15	6	15.92	20	29	29.39	24	102	12.27	32	114	6.79	45
100	12.16	8	6	15.92	14	94	18.99	19	39	34.83	27	9	15.6	31	105	7.86	41
5	15.92	7	94	18.99	14	47	37.02	19	51	39.07	25	96	19.27	31	3	11.57	40
93	18.99	7	38	34.83	17				59	39.97	23	30	29.35	36	97	19.34	42
19	23.52	8	47	37.02	15				74	41.65	22	54	39.54	28	21	23.6	40
28	29.39	7	67	39.07	15							55	39.54	27	31	29.3	40
36	35.73	6	85	43.45	15							60	39.99	27	40	34.72	39
45	37.07	6	87	49.6	13							76	41.88	32	48	37.09	35
66	39.2	7	91	51.44	8										68	38.94	42
53	39.67	8													61	39.9	40
58	40.11	8													75	41.68	42
73	41.37	4													80	44.53	42
81	46.91	4													88	48.5	42
86	49.7	6															
83	49.75	5															
90	51.44	5															

T5			**T6**			**T7**			**T8**			**T9**		
#	**Place**	**Alt**	**#**	**Place**	**Alt**	**#**	**Place**	**Alt**	**#**	**Place**	**Alt**	**#**	**Place**	**Alt**
15	18.71	50	111	0	69	113	0.52	76	113	0.52	87	***	***	***
25	21.83	55	106	6.92	65	2	11.83	75	2	11.83	85			
32	29.28	55	1	11.95	65	99	18.43	75						
41	33.96	55	98	19.19	65	16	18.48	75						
49	37.2	50	42	34.55	66	27	24.04	73						
69	38.94	50				35	29.33	75						
56	39.46	49												
62	39.8	52												
89	48.69	50												

Measurement number

Place Distance along transect in km. The start of the transect (0 km) is upstream in Vide. The transect ends 2 km before the Atlantic Ocean at 52 km.

Alt Altitude in m a.s.l. of terrace surface

Portugal

T0			T1min			T1max			T2			T3			T4			T5			T6			T7			T8			T9		
#	Place	Alt	#	Place	Alt	#	Place	Alt	#	Place	Alt	#	Place	Alt	#	Place	Alt	#	Place	Alt	#	Place	Alt	#	Place	Alt	#	Place	Alt	#	Place	Alt
115	2.6	9	130	7.5	17	140	10.34	19	117	2.51	24	116	2.67	32	118	2.25	42	119	2.11	55	120	2.02	66	121	2.05	80	157	18.33	84	149	15.48	95
128	7.5	9	140	10.34	12	151	18.45	18	160	22.79	25	123	4.13	31	124	4.18	40	135	8.59	53	125	3.97	69	127	5.05	76						
139	10.31	8	143	16.58	13	159	23.06	19	208	29.28	25	132	6.89	32	131	7.25	43	142	10.74	53	133	7.05	65	134	7.05	75						
144	16.27	8	151	18.45	12	207	29.33	19	215	30.06	24	152	19.03	32	141	10.55	39	148	15.68	50	136	8.67	67	138	10.74	78						
150	18.45	8	159	23.06	14	214	30.50	19	218	30.36	25	161	22.69	32	153	18.47	40	154	18.52	52	137	10.64	67	146	16.06	78						
158	22.97	8	207	29.33	15	221	31.85	21	176	47.92	24	164	23.02	30	209	29.23	40	163	22.77	50	147	15.68	65	156	18.43	73						
206	29.02	8	214	30.5	13	201	33.02	17				202	33.14	30	222	32.11	40	210	28.88	56	155	18.52	66	205	33.46	74						
213	30.3	7	221	31.85	14	184	43.98	19				177	45.75	30	203	33.14	38	216	30.1	55	211	28.71	70									
220	31.77	7	201	33.02	16							183	47.47	30	197	36.37	44	223	32.39	55	217	29.98	65									
200	32.79	7	195	36.34	16										191	38.82	40	204	33.25	54	219	30.19	64									
194	35.73	7	190	39.02	15										188	40.91	39	198	36.53	54	224	32.27	67									
189	39.05	8	184	43.98	13										186	43.3	40	192	38.89	52												
187	41.95	7	182	45.29	13										179	46.44	40	174	50.7	50												
185	43.3	6	175	48.28	9										171	51	36	169	50.96	52												
181	45.33	7	180	49.76	9										170	51.39	40															
178	47.24	6																														
172	48.89	6																														
173	50.82	5																														

Appendix 4 Field data samples OSL-dating

Nr	Code	Name & location	Terrace number	Date of retrieval	Time	E	N	Place where sample taken within terrace	Amount of sediment visible in enclosure	Altitude surface terrace	Altitude base terrace
1	CDV1	Chan de Vide 1	T7	24-5-2007	12:42	550733	4659520	3 m under surface	12 m	76 m	68 m
2	CDV2	Chan de Vide 2	T7	24-5-2007	13:04	550733	4659520	1,0-1,5 m above base	12 m	76 m	68 m
3	CDV3	Chan de Vide 3	-	24-5-2007	14:00	550610	4658837	2 m under surface	17 m	32 m	~15 m
4	CDV4	Chan de Vide 4	-	24-5-2007	14:06	550610	4658837	8 m under surface	17 m	32 m	~15 m
5	ST1	Salvaterra 1	T6	24-5-2007	16:21	541000	4659789	0,5 m above base	10 m	65 m	45-50 m
6	ST2	Salvaterra 2	T7	24-5-2007	17:00	541122	4660046	0,10 cm above base	8 m	75 m	65 m
7	OL1	Oleiros 1	T6	24-5-2007	18:01	?	?	3 m above base	8 m	60 m	46 m
8	OL2	Oleiros 2	T4	1-6-2007	12:43	545482	4660157	1,20 m under surface	6 m	40 m	34 m
9	OL3	Oleiros 3	T4	1-6-2007	13:26	545275	4660434	6 m under surface	8 m	41 m	33 m
10	OL4	Oleiros 4	T6	1-6-2007	15:00	546320	4660371	1 m under surface	9 m	60 m	51 m
11	OL5	Oleiros 5	T6	1-6-2007	15:30	546386	4660371	0,20 m above base	9 m	60 m	51 m
12	GOIAN1	Goian 1	T4	1-6-2007	17:02	517672	4646197	1 m above base	7 m	42 m	35 m
13	GOIAN2	Goian 2	T4	1-6-2007	17:50	517752	4643250	1,5 m under surface	7 m	42 m	35 m
14	FURNA1	Furna 1	T1	21-7-2007	13:38	523921	4647228	2 m above base	9 m	17 m	8 m
15	FURNA2	Furna 2	T1	21-7-2007	14:15	523867	4647219	1,5 m under surface	9 m	17 m	8 m

Altitudes in meter above sea level. Code refers to sample code. Name and location refer to place where sample was taken. This is also the full name for the sample.

Appendix 5

Optical Luminescence Dating of fluvial terraces from Miño river.

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Experimental procedures.

Samples were taken by pushing stainless steel cores into the sediment exposed wall. Under subdued safe light, the sample was taken out from the cores, saving the central part for luminescence analysis. Sample from both core's extremes was used for complementary analyses (humidity content and high resolution gamma spectrometry). The central part of the core was etched first with HCl for removing carbonates and then with NaOH for removing organic matter. After sieving the sample, the fraction of size between 0.180 mm and 0.250 was separated and prepared for luminescence measurements. Preparation consists on several etchings with diluted HF for removing feldspars. Feldspar content is tested according procedures described in Mauz & Lang (2004). Once the feldspar content is acceptable for analysis, the grains are measured for calculating their Equivalent Doses.

Purified quartz grains were mounted on Al discs using silicone spray. For the OSL measurements, a Risø reader model TL/OSL-DA-15 was used. Optical stimulation was provided by Nichia blue light-emitting diode arrays providing 38 mW (100% power at 470 nm). An UV emission band was obtained using a Hoya U340 filter. The reader is equipped with a $^{90}Sr/^{90}Y$ beta source which provided 0.140±0.003 Gy/s during all the set of measurements. For calibrating the source, an artificially irradiated quartz (5 Gy) provided by Risø was employed.

SAR procedures (Murray & Wintle, 2003) were used for measuring all the samples. SAR measurements were performed at 125ºC, during 40 s. Prior to the measurements, samples were preheated to 260ºC during 10 s. Test dose signal response were measured at the same temperature after a cut heat step at 220ºC. Preheat temperature was chosen after performing preheat temperature tests for all the samples. Equivalent doses were calculated by interpolation from *Analyst* software integration data (1% systematic error incorporated).

Data Analysis.

The interpolated equivalent doses were statistically studied in order to obtain the most accurate Paleodose (Pd) from the measured distribution of Equivalent Doses. We follow the procedure described in Bailey and Arnold (2006). According to this procedure, all the Paleodoses were calculated from their correspondent Equivalent Doses distribution using the Central Age Model (CAM) (Galbraith et al., 1999; Galbraith et al., 2005). The calculated Paleodoses are shown in Table 1.

	Paleodose (Gy)	Std. error	Overdispersion (%)	Model
07/007-CDV1	300	12	10	CAM
07/008-CDV2	409	16	9	CAM
07/009-CDV3	0,49	0,056	35	CAM
07/010-CDV4	3,52	0,11	9	CAM
07/011-ST1	301	5,74	0	CAM
07/012-ST2	397	18	9	CAM

Table 1. Calculated Paleodoses.

Annual Dose calculation.

Measurement of radioactive elements activity contribution to the annual dose, high resolution gamma spectrometry analysis were made in all the samples. The inner part of the cores was selected in order to avoid recent changes in elements concentration. The sample is sieved if the grain size is larger than 0.5 mm and burned at 450ºC for 20 hours. About 150 g of the burned samples are then stored in a sealed flask during 30 days for radon reequilibration. High resolution gamma spectrometry analysis were done at Laboratorio de Radiactividad Ambiental, University of A Coruña, with a Camberra XTRA gamma detector (Ge Intrinsic) during 46-68 hours counting time.

High resolution gamma spectrometry analysis are the only method to check the secular equilibrium condition in the radioactive chains ^{238}U, ^{232}Th and ^{235}U. This condition is necessary for an accurate calculation of the annual dose. When secular equilibrium is not the case, the annual dose calculation needs to take into account the disequilibrium measured (Olley et al, 1996). As the disequilibrium is usually consequence of mobility of the radioactive elements after deposition, it is very difficult to know when equilibrium condition was broken.

Results show that all the samples are in secular radioactive equilibrium except the 07/008-CDV2 sample. In order to know the initial radioactive activities of this sample, it was etched with concentrated HNO_3 and measured again. If the change in activities were due to a postdepositional crust containing radioactive elements, then the etching should solve away this crust, leaving only the quartz grains which should be at secular equilibrium. But results (see table 2) show that the lixiviated sample is still far from the secular equilibrium ($^{238}U/^{226}Ra=1$). Then no reliable annual dose can be calculated for the sample 07/008-CDV2. We can, at least, suggest a minimum age given by the actual radioactive elements activities and a maximum age calculates using the activities after the leaching. If we take into account that this sample must be older than the 07/007-CDV1, given their relative positions, it is clear that the minimum age has no geological meaning. The suggested maximum age does fit the requirements of relative chronology, but it must be taken only as an approximate age.
For the rest of the samples, annual dose was calculated according to Adamiec and Aitken (1998). Annual Doses and derived ages are shown in Table 2.

Sample	^{238}U (Bq kg^{-1})	^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})	Dry Beta (Gy ka^{-1})	Dry Gamma (Gy ka^{-1})	Water Content (wt %)	Annual Dose (Gy ka^{-1})	Pd (Gy)	(n)	Age (ka)
07/007-CDV1	22,9 ±5,5	29,2 ±2	42,8 ±2,2	219 ±21	1,15 ±0,13	0,95 ±0,09	6,9	2,07 ±0,19	300,00 ±12,00	10	144,87 ±14,21
07/008-CDV2	52 ±14	127 ±7	18,2 ±1,1	326 ±31	1,82 ±0,23	1,64 ±0,17	8,6	3,07 ±0,32	409,00 ±16,00	9	133,05 ±14,85
07/008-CDV2 Lixiviated	28 ±9	77 ±4	14,2 ±0,9	309 ±29	1,37 ±0,16	1,10 ±0,11	8,6	2,22 ±0,23	409,00 ±16,00	9	183,99 ±20,00
07/009-CDV3	24,5 ±6,6	33,1 ±2	38,5 ±2	707 ±66	2,33 ±0,24	1,32 ±0,12	8,3	3,34 ±0,31	0,49 ±0,05	10	0,15 ±0,02
07/010-CDV4	18,7 ±5,6	30,9 ±1,8	29,4 ±1,5	670 ±62	2,13 ±0,22	1,16 ±0,11	8,9	2,89 ±0,28	3,52 ±0,11	10	1,22 ±0,12
07/011-ST1	10,6 ±4,6	12,2 ±1,1	12,3 ±1,2	29 ±6	0,26 ±0,06	0,27 ±0,04	11,8	0,59 ±0,08	301,00 ±6,00	7	506,25 ±66,81
07/012-ST2	17,1 ±5,7	22,3 ±1,4	67,4 ±3,3	110 ±11	0,92 ±0,11	1,10 ±0,09	11,5	1,85 ±0,17	397,00 ±18,00	8	214,18 ±21,71
07/013-OL1	23,8 ±6,3	32,1 ±1,9	63,6 ±3	277 ±26	1,41 ±0,15	1,28 ±0,11	10,8	2,42 ±0,22	--	10	--

Table 2. Significative radioactive elements activities. Annual dose and derived ages.

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Appendix 6 Photographs fieldwork

Plate 1. The Miño river around As Neves. On top of the granite T3 is visible.

Plate 2. Typical vineyard on river terrace in Galicia. Portugese mountains on background.

Plate 3. Chan de Vide. Holocene sedimentation, likely due to upstream deforestation.

Plate 4. Ongoing road constructions in Galicia open up new enclosures. T6 in Salvaterra. White band is not fluvial material in situ but are pebbles fallen down from above.

Plate 5. Destruction of alluvial terraces through terracing for viniculture. Porto, Galicia.

Plate 6. Transport and mobile home during the fieldwork period March-June. A Veiga do Louro, Galicia.

Plate 7. The art of wall recognition. Usage of local fluvial cobbles for wall construction betrays presence of alluvial terraces.

Plate 8. Terrace scarp T5, Estas, Galicia. Note size of house to appreciate the vastness of T5.

Plate 9. Mouth of the Miño as seen from Tabagon. Right side is Monte Santa Tecla, A Guarda.

Plate 10. T7. Quarry Chan de Vide, Galicia.Predominantly sandstone and quartz(ite) conglomerates in a clayey to loamy matrix Measuring rod is 2 m high.

Plate 11. Quarry Chan de Vide, Galicia.

Plate 12. T0 Portugal. Size cobbles 7 to 40 cm.

Plate 13. Paleochannel incised in weathered iron-rich granite. Monção, Portugal. Height enclosure 4 m. Terrace is T5.

Plate 14. Enclosure of T3 or T4. Quarry Oleiros, Galicia. Note fining upward sequences and loamy layers.

Plate 15. From bottom to top: weathered granite (reddish yellow), paleosol developed in fluvial terrace (dark brown), fluvial sands mainly quartz (red), sandstone and quartz(ite) conglomerates (yellow), contemporary soil. It is clear that this fluvial terrace is polygenetic. T5 Monção, Portugal.

Plate 16. Furna, Portugal. T1. Note cross-bedded sands and iron fragipan. Pebbles size 7 cm.

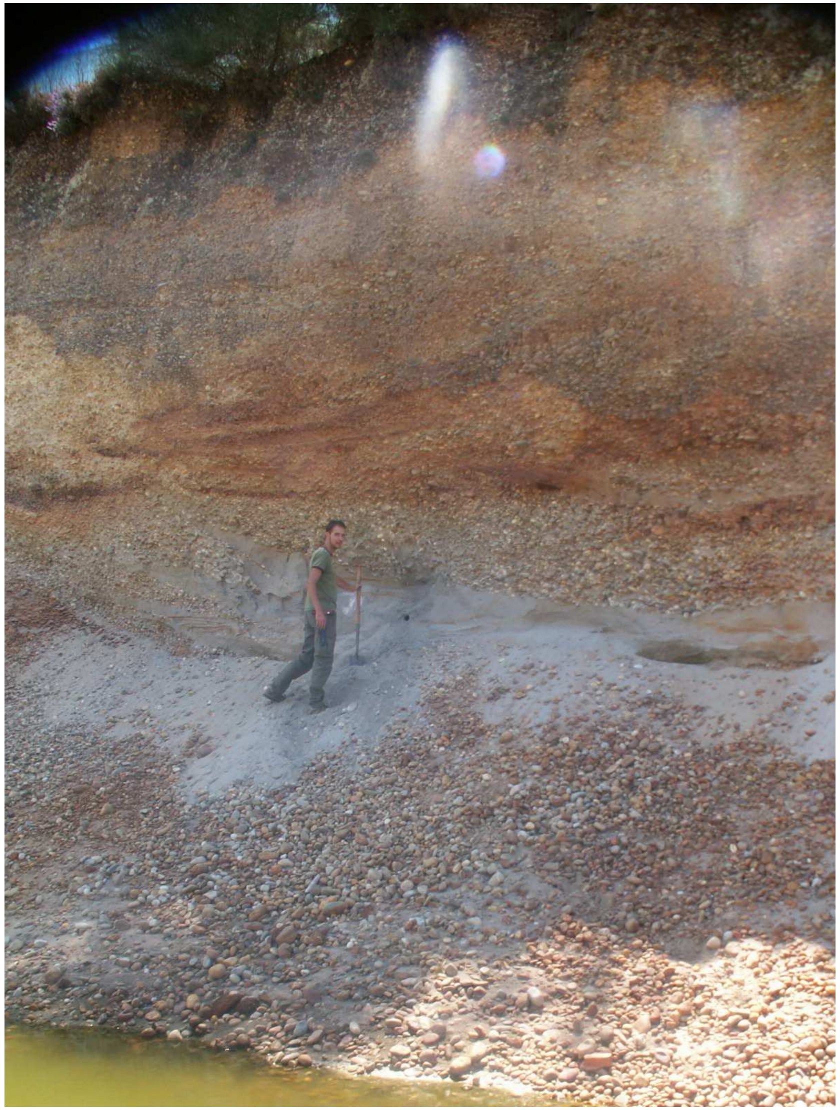

Plate 17. Quarry Furna, Portugal during sampling for OSL-dating. Entire T1 terrace visible. Photo 14 is a close-up of this terrace.

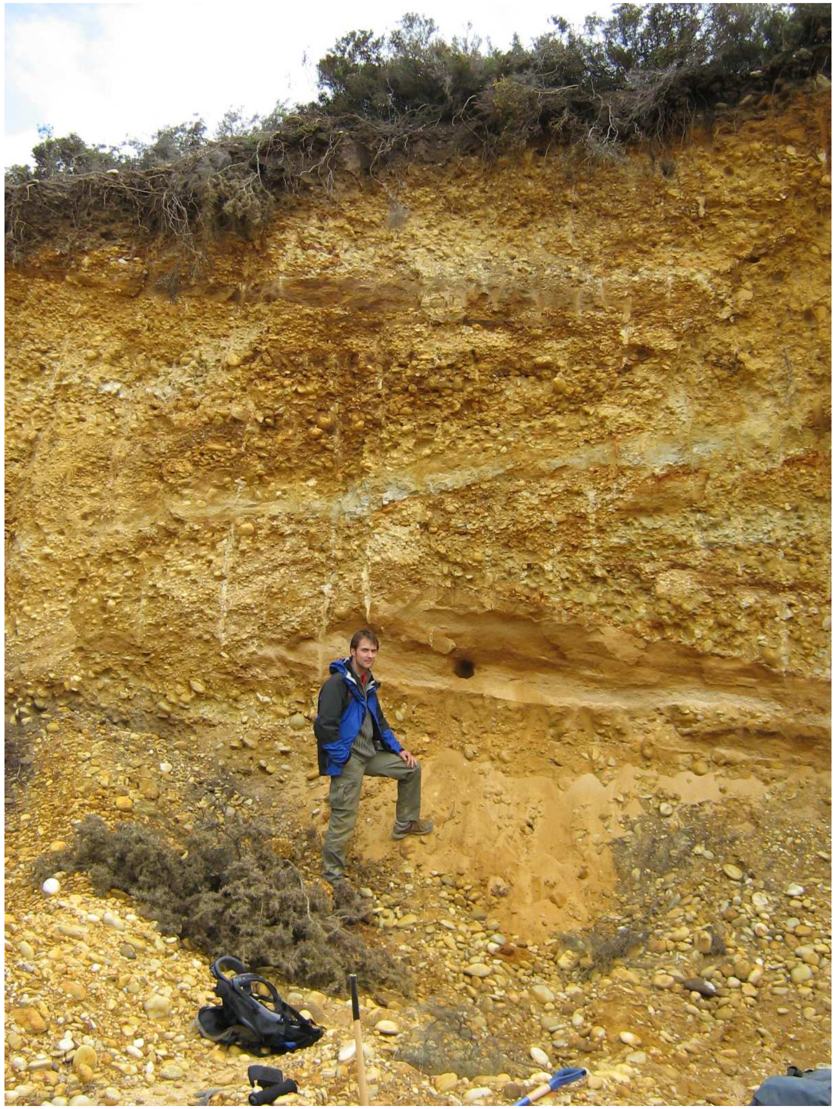

Plate 18. T4 Goian, Galicia during sampling for OSL-dating. The hole shows where the aluminium shaft was inserted. Note cross-bedded sands.

Plate 19. T4 Goian. Note transition to finer sediments on top.

Plate 20. T4 Goian. Saprolite-terrace transition.