

Landscape Genesis

Marine and River Terraces
Around the Miño Estuary

-MSc Thesis-

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ABSTRACT

This report on marine and fluvial terraces near A Guarda, southern Galicia is based on extensive fieldwork; ancient sea level-; and gravel analysis. This research identifies 11 different terrace levels along the Spanish coast, 16 along the Portuguese coast and 13 terrace levels in the O Rosal valley. Nine terrace levels seem to correspond, ranging form 7 to 60 m in altitude. Probably these terraces have all been formed around sea level high-stands. The marine terraces were formed by continuous erosion during inter-glacial periods, while the fluvial terraces are thought to be formed by incision at the turn of inter-glacial to glacial circumstances. Two fluvial terrace levels without marine equivalents are found, these are formed by an increase in sediment influx during transition periods from inter-glacial to glacial circumstances, and subsequent incision when the equilibrium returned and more clean water became available. The well corresponding terrace levels imply that differential uplifting between the O Rosal valley, Spanish and Portuguese coast did not take place since the formation of the 60 m terrace. However, sea level analysis shows that uplift is present in the area, and possibly also periods of subsidence occurred in the past. A conservative sea level – terrace correlation seems to be the most convincing. In this scenario the terraces are formed during sea level high-stands between 125 and 1050 ka. This leads to a variable uplift rate between -0,086 and 0,13 mm/y. The O Rosal valley shows strong indications of basin lowering and tectonic tilt. At least three blocks are found which seem to be tilting independent of each other. Topographic analysis show the tilting probably is still active, though it has been more active in the past.

Foreword

This is an MSc thesis for the study Land Dynamics, the geomorphology specialisation of the Master Soil Sciences at the Wageningen University, the Netherlands. This research is part of a Phd research of Willem Viveen, and has been undertaken at the University Institute of Geology Isidro Parga Pondal of the University of A Coruña, lead by Juan Ramón Vidal Romaní.

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I would like to thank the people tremendously who helped me in any way with my thesis.

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The second person I owe a lot to is my other supervisor, and director of geological institute Isidro Parga Pondal, Juan Ramón Vidal Romaní, for showing me different kind of ancient beach, dune and colluvium deposits. He gave me a place to work in the institute, and helped me out by giving feedback, additional information and letting me use the facilities of the geological institute.

I would like to thank my supervisor Jeroen Schoorl for arranging this thesis-possibility and giving his insight on the study area during fieldwork.

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The other people working at the geological institute Isidro Parga Pondal I would like to thank for helping me out when I needed something, and being friendly.

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Table of Contents

1. Introduction

This research investigates the marine and fluvial terraces near the Miño estuary. The study area lies in the province Pontevedra in Spain (S) and the district Viano do Castelo in Portugal (P), the Miño is the border between the two countries and enters the sea at A Guarda (S) and Caminha (P). For this analysis the area has been subdivided in three different parts, the Spanish coast, the Portuguese coast and the O Rosal valley.

In this research extensive fieldwork is done to get a complete picture of the terraces in the study area. The terraces are compared to the terraces found by other authors, and to the terraces found in other parts of the study area. Information of the different terraces is used to make a connection between the marine and fluvial terraces in the area. Although already some authors described fluvial terraces (Nonn, 1967; Cano Pan et al., 1997; Butzer, 1967; Yepes Temiño, 2002) and marine terraces (Texier and Meireles, 1997; Cano Pan et al., 1997; Butzer, 1967) in the study area, so far very little research has been done on the link between fluvial and marine terraces.

As dating of sediment is a big problem in the area, it is very hard to get a complete understanding of the landscape genesis or find hard proof for age related hypotheses (Alonso and Pagés, 2007). In this report the terraces which are probably related, are compared to former sea level and climate data to come to an understanding of the processes behind the formation of the terraces. Although some assumptions have been made, this leads automatically to some implied minimum ages of different phases of terrace formation and the deposition of the sediments which are found below them.

In addition, in the O Rosal valley, analysis of the gravel deposits and topography has been done to find more information on the deposition of the sediments and formation of the terrace sequences. Features found in the field are connected to processes described in literature to come to a full understanding of their meaning.

This report is subdivided in seven chapters. In chapter 2 a summary of the study area is given, with general information on the location (i), vegetation (ii) and climate (iii); and subsequently the geological back ground of the study area (iv), possibilities for dating (v) and a short discussion of terrace formation is discussed. Chapter 3 mentions the research questions of this research and in chapter 4 the methodology is summarized.
In chapter 5 the results are presented. First the marine terraces levels along the Spanish coast are discussed, the sediments which are found on the terraces are mentioned, and a comparison is made between terrace levels mentioned by other authors. From this information the most reliable terrace levels are drawn. Subsequently in section 5.2 the same is done for the marine terraces on the Portuguese side of the study area, and in section 5.3 fluvial terrace levels and sediments in the Rosal valley are discussed and compared to information found in literature. In section 5.4, the terrace levels of the Spanish coast, Portuguese coast and O Rosal valley are compared and connected, just as the sediment found on these terraces. In section 5.5 an analysis is done based on terrace height and sea level and climate data. A possible event is given for every terrace. Section 5.6 discusses the deposits and exposures in the O Rosal valley, and explains the meaning of the structures found. In section 5.7 the general topography and possible tectonic activity is shortly discussed. Chapter 6 forms the general discussion, which mostly focuses on the methodology as the results are discussed in the chapters itself. Chapter 7 is the conclusion of this research, in which all the results are shortly summarized. Chapter 8 gives some recommendation for future research. At last a reference list of used literature is given.

2. Study area

In this chapter I give a summary of the characteristics of the study area. I will shortly give some information on the geographical setting (2.1); the vegetation (2.2); the climate (2.3); the geological background of Galicia (2.4); dating possibilities in the study area (2.5) and the terraces found in the area are shortly discussed (2.6).

2.1 Geographical setting

The study area lies at the border of Galicia (NW Spain) and Portugal, in southern Europe around 41°54'23 N - 8°51'48 O. The study area lies in the province Pontevedra in Spain and the district Viano do Castelo in Portugal. The study area is limited by the Atlantic Ocean in the west, Oia in the north, Viano do Castelo in the south, and the flank of the O Rosal valley in the east and north.
Directly along the coast steep slopes are found. The altitude rises from sea level to 500 m.a.s.l. in 1700 meter on the Spanish side, and from sea level to 400 m.a.s.l. in 3500 m on the Portuguese side of the study area. The top of the area is quite flat again. The main part of the O Rosal valley is relatively low and flat, with altitudes between sea level and 60-70 meter with steep flanks on the west, north and east side of the valley.

2.2 Vegetation

The normal vegetation in the study area during inter-glacial periods are deciduous trees like oak (Desprat et al., 2009). However most of them have been cut to make room for agriculture, or houses. The present vegetation consists generally of some agriculture close to the ocean, followed by small prickly bushes, with an occasional eucalyptus forest. In the O Rosal valley mostly agriculture and small villages are present, with some small forests in between. The steep slopes on the edge of the O Rosal valley consist mostly of eucalyptus trees. On the Portuguese side of the study area, the lower parts are used for agriculture and expanding villages with some dune areas found with deciduous trees near Caminha and Vila Praia de Âncora. On the higher parts almost solely eucalyptus trees are found.

2.3 Climate

The climate in the study area is warm and wet with an average annual precipitation in the Rias Baixas between 1315 mm and 1930 mm, and an average temperature between 10,1 and 18,5° Celsius and an absence of frost ("O Baixo Miño", 2010).

Paleo climate

It is believed that during ice ages the climate was cold and dry in the NW Europe, with little vegetation; while during inter-glacial periods the climate might have been similar to today's, with large forests of deciduous trees (Cheddadi et al. 2005, Desprat et al., 2009, Stemerdink, 2010, Tebbens et al., 2000). Butzer (1967) and Blanco-Chao et al. (2002, 2007) agree that was not been any land ice close to the ocean. However periods of snow and ice were present in the study area (Butzer, 1967; Blanco Chao et al. 2002, 2007). Probably during glacial periods rivers were almost dry in winter, while in spring and summer snow melt caused large discharges (Tebbens and Veldkamp, 2001; Stemerdink, 2010). Also during the transition from glacial to inter-glacial periods, snow melt is believed to have caused large discharges in NW Europe (Tebbens and Veldkamp, 2001).

2.4 Geological background

Central and western Galicia comprise of the fold zone of the Hesperian massif, the name of the Hercynian or Variscan orogenic belt of the Iberian peninsula. This massif was formed when the Europe and North America crushed in to each other in the Devonian and Carboniferous (+/- 417-290 Ma), closing the Iapetus Ocean (Tebbens and Veldkamp, 2001). During this time present Precambrian and Palaeozoic rocks were deformed and granite intrusion caused contact metamorphosis of the present meta sediments and created quartz-, porfiric-, diabase-, and pegmatite veins (Yepes Temiño, 2002). The oldest granite, close to mayor faults was transformed to ortho-gneiss while the younger granite underwent less metamorphosis. The hard rock in the study area ranges from granite, to gneiss and mica schist, formed by low metamorphosis during the late Palaeozoic. The different hard rocks are found in belts ranging more or less N-S through the study area (den Tex, 1981). Along the Cantabrian coast in Asturias also sedimentary rocks can be found, these are folded marine deposits of the Iapetus Ocean (Tebbens and Veldkamp, 2001). The closing of the Iapetus sea was accompanied by folding and faulting. First trend folding took place along N-S axes, then recumbent folding occurred along N-S and E-W axes, followed by refolding along NNE axes (den Tex, 1981). During the deformation also ENE-WSW faults were formed (Yepes Tomiño, 2002).

In the Triassic (230 Ma) rifting started in the Hercynian Massif, causing America and Europe to drift apart in the Jurassic and Cretaceous, continuing into the Cenozoic (Tebbens and Veldkamp, 2001). The rifting created many N-S faults in the area (Yepes Temiño, 2002). As also the Iberian and Eurasian plate separated, the Bay of Biscay opened up (Yepes Temiño, 2002).

In the Tertiary most of the Hercynian massifs were flattened out to a peneplain, during a long tectonic stable period, with rapid chemical weathering in a tropical climate (Tebbens and Veldkamp, 2001). Presently a former peneplain can be recognised at 550-600 m in Galicia (Yepes Temiño, 2002). From the late Cretaceous on, the Iberian and Eurasian plate started to move together. As the Iberian plate crushed into the Eurasian plate in the Palaeogene and beginning of the Miocene, the Pyrenees were formed. The same collision caused the Iberian plate to subduct under the Bay of Biscay, uplifting the Cape de Ortegal, and forming the Cantabrian mountain range (Yepes Temiño, 2002). From the Miocene onwards in the Pliocene the rias along the Galician coast started to develop as a result of uplifting in combination with local subsidence, probably caused by a rift valley in front of the coast (Pannekoek, 1966).
During the Alpine orogeny, many of the Hercynic faults were reactivated (Butzer, 1967; Yepes Temiño, 2002) and the renewed uplift caused rivers to incise deeply in their river beds (Tebbens and Veldkamp, 2001).

In the Quaternary the Hesperian massif was situated in a colder environment and was influences by strong fluctuations in climate, glacial periods and inter-glacial periods. These climate fluctuations were accompanied by large fluctuations in discharge and sediment availability in rivers, and changes in sea level; this caused the rivers to fill up their river beds and later incise again in their sediments (Tebbens and Veldkamp, 2001) creating terraces along the rivers and in the Tertiary basins. The sea level fluctuations caused marine terraces to be formed in the study area (Butzer, 1967; Texier and Meireles, 1997), while during more recent cold periods many colluvial deposits were formed in the area (Blanco Chao et al., 2003; Butzer, 1967; Cano et al., 1997).

Faults running E-W in the Cantabrian mountains continue into Galicia. In the Ourense Corridor, in the east of Galicia, they are deflected to a NNE-SSW to N-S direction, with lateral ENE-WSW faults. Due N-S compression, lateral movement takes place along a N-S fault, in which the eastern part relatively moves N in relation to western Galicia. Along the faults, basins are formed, filled with Tertiary sediments. Another effect of this compression are the thrust faults along which the rio Lima and rio Miño flow, by which Portugal is pushed under Galicia (Vegas, 2009). These Tertiary basins, related to a horst graben structure form a typical "piano-keys with mounts and depressions" landscape in Galicia (Vegas, 2009; Butzer, 1967; Blanco Chao et al., 2003; Nonn, 1967; Alonso and Pagés, 2007; Yepes Temiño, 2002).

It is believed the Louro valley is a submerged basin (Butzer, 1967), and possibly the O Rosal valley as well.
In general most rivers seem to follow the faults in the area. The Miño and the Rio Lima run ENE-WSW, and also the Rio Tamuxe, Rio Louro, Rio Brina, Rio Furnia flow quite straight in an N-S direction. Although Nonn (1967) and Blanco Chao et al. (2003) find the tectonic situation stable at the moment, Carvalho (1981, in Granja, 1999) found a fault in a Miño deposit, which implies tectonics are still active, as the deposit is formed in the Quaternary (Carvalho, 1981 in Granja, 1999). Also Viveen et al. (2010, personal communication) found several faults in Miño deposits close to the study area, and recent earthquakes (1995 and 1997) imply that tectonics are indeed still active (Perez, 1998; Vegas, 2009).

2.5 Dating

A big problem in the area is that it is very hard to date sediments, most commonly used methods are limited or not usable. For example, because of the granite basement, the soils are quite acid and shells and bones quickly dissolve, limiting the possibility for preservation (Butzer, 1967). In addition, granite is radioactive by nature, which makes U-Th-Pb dating impossible due to high levels of background radiation, and carbon-14 dating is often not possible due to the age of the sediments (Alonso and Páges, 2007). However, Cano et al. (1999) did successfully use the method to date some alluvia and colluvia along the coast but these are younger of age. In this research preliminary information of OSL and Berilium-10 dated samples is used from Viveen et al., which do look promising, although the insecurity ranges are still large. OSL-dating was invented in 1985 (Berger; Jacobs and Roberts, 2009), though still new techniques, applications and improvements are made (Tanaka et al, 1997; Lucas et al., 2007). While also ^{10}Be-dating is still under development (Dickin).

2.6 Terraces

Several authors already wrote about fluvial terraces along the Miño (Butzer, 1967; Cano Pan et al.,1997; Nonn, 1967; Teixeira, 1952; Yepes Temiño, 2002;). Nonn (1967) finds levels up to 95 m high, and Yepes Temiño (2002) even mentions old terraces at 1040-1060 m, subdivided in 16 different steps, just 50 km upstream of the estuary.
Marine terraces have been identified along the Spanish coast by Butzer (1967) up to 49 m, and along the Portuguese coast by Teixera (1952) and Texier and Meireles (1997). Texier and Meireles (1997) find 10 different terrace levels up to a height of 140 m above present sea level. The findings of these authors will be discussed in more detail in Chapter 5.
Butzer (1967) did research along the Spanish coast and the lower Miño and was able to connect three fluvial terrace levels between the coast and the lower Miño, in which the highest terrace is though to be an ancient river passage at 44-49 m.

Marine terraces are believed to be formed during periods of stable sea level (Hearty et al., 2007, James et al., 1971). In this research the focus will be on the sea level high-stands, as these are the largest and most recognizable periods of stable sea level. A staircase of marine terraces will be preserved in the area when the uplift rate is high enough that a subsequent sea level high-stand does not reach the former terrace anymore (James et al., 1971; Wilson et al., 1998). If the sea level rose above a formed marine terrace, the marine sediments will be flushed away; consequently the possibility ancient beaches (either gravel or sand) a preserved on top of the marine terraces is also small (Wilson et al., 1998).

Fluvial terraces are formed by incision of a river in either its own sediment (fill terrace), or in its own bedrock (strath terrace). Incision takes place at places where the energy of the river increases. This can be due to i) base-level drop; ii) tectonic uplift; iii) decrease in sediment availability; iv) increase in discharge. Deposition takes place because the energy of a river decreases. This can be caused by i) base-level rise; ii) tectonic subsidence; iii) increase in sediment availability; iv) decrease in discharge (Merritts et al., 1994; Pazzaglia, 2010; Tebbens and Veldkamp, 2001).
Base level fluctuations in the study area are influenced by fluctuations in sea level, sediment availability and discharge are strongly influenced by vegetation, land-use, and erosional / depositional processes upstream (Cano Pan et al., 1997; Schumm and Parker, 1973; Summerfield, 1991; Tebbens and Veldkamp, 2001).

3. Research questions

3.1 Research aim

The main aim of this research is to get a better understanding how the landscape is formed around A Guarda. The goal is to give a reconstruction of the formation of the landscape and an explanation of the different processes which influenced this formation. The focus of this research is on the fluvial and marine terraces, though also other landscape forming processes are described when they are encountered.
In this report I will try to answer the following research questions.

3.2 Research Questions

Main Research Question:

How are the marine and fluvial terrace sequences formed as we see them now, and which processes were behind the formation of the these terraces?

Research Questions:

- Where can terraces be found and how are they composed?
- Is there a link between the marine terraces and the lower Miño terraces?
- What are the most probable causes and processes of terrace formation?
- Which other processes for landscape formation are important in the study area?

4. Materials and methodology

4.1 Materials

During this research several materials have been used. Below all the materials are listed and their use has shortly been explained.

Table 4.1: Materials used in this research

Tools	Purpose
Tools used during the field work	
Geological Hammer	- to break gravels and rocks for rock determination - to clean exposures to get a better view on possible structures - to take rocks out of exposures - to take soil samples out of exposures
Shovel	- to dig away thin layers of soil, or colluvium to - to clean exposures to get a better view on possible structures
GPS	- to get the coordinates and an indication of the altitude in the field. - to measure imbrication direction to measure tilt direction
Clinometer	- to measure the slope on steeper or less obvious terrace levels - to calculate the height of exposures
Pen, pencil, exposure sheets and notebook	- to note down detailed descriptions and make sketches of exposures.
Topographical maps	- to orientate and find the right location
Tools and software used during the reporting and analysis	
Laptop	- to use the following software packs
Open Office software pack 3.2	- to write the report - to make some calculations and UTM/Lat-Long transformations
Microsoft Office 2003	- to write the report - to make analyses regarding the terrace height, uplift rate, sea level fluctuation and climate - to make presentations
gMapMaker v0.7.3.6	- to download digital aerial photos
ArcGis 9.3	- to visualise the found field data - to analyse the found field data
Paint	- to visualise data
Adobe Photoshop	- to visualise data
Mozilla Firefox 3.6.13	- to find for more available information on the subject
Tools used as source of information	
Geological maps (1962 & 1972)	- to find out where terraces have been found already - to find out which parent materials are present in the area
Topographical maps	- to find possible terrace and their altitude - to find the way
DEM	- to find possible terrace levels and their altitudes - to find possible faults
Scientific articles and general available information	- to get a better understanding on the subject - to come up with explanations of the subject
Google Earth	- to orientate, find locations and measure distances

4.2 Methodology

4.2.1 Obtaining information

In this research I had the luck that my supervisor, Ir. Viveen, has already been working in the area for a long time and has obtained a lot of information over the years. Aerial photographs from 1956 and 1984 were available for the Spanish part of the study area, as well as a detailed Digital Elevation Model (DEM) and several digitised geological maps from 1972, from the Instituto Geológico y Minero de España, part of the Spanish ministry of Industry and Energy. On the Portuguese side of the study area unfortunately less information was available. A geological map from 1962, issued by the Instituto Geográfico e Cadastral, and aerial pictures from 1958 were available for the area around Caminha. But from the area further south, nothing was present.

To be able to find good terrace levels in the area, and make promising and practical transects two topographical maps scale 1:25.000 have been ordered from Instituto Geográfico Português. Also digital aerial photos of the whole study area have been downloaded.

Capturing and georeferencing aerial photos
At the moment, many freely available aerial photographs are available, especially for the developed world. The USGS offers different kind of maps, though the more reliable are unavailable for non-US citizens. Therefore imagery from maps.google.com was downloaded with Gmapmaker and Noni map view. Because there were problems with geo-referencing of the images, the Lat/Long coordinates were transformed to UTM 1950 29N coordinates (Dutch (2005; Mummery; Earthpoint (2010)). Subsequently the geo-referencing was improved manually in ArcGis software package 9.3.

4.2.2 Identification of the terraces

As a preparation for the field work first possible terraces were identified with use of a Digital Elevation Model; Topographic maps with contourlines on a scale 1:25.000; aerial photographs, geological maps from Instituto Geológico y Minero de España (1972) and Instituto Geográfico e Cadastral (1962); and literature which has been written on the area. For Spain DEM and slope maps with a grid size of five meter were used, these were unfortunately not available for the Portuguese side of the study area. So for this part the interpretations were done solely with the use of the topographical maps and descriptions of former researchers.

The last few years quite some construction has been going on in the study area. Therefore photographs from 1956 were used in case it was not sure whether an area was excavated or not. The older images give a more authentic picture of the height differences. In addition, Google Earth was used to find possible new exposures.
With this information transects were made, and it was found out if the first interpretations were correct. By walking, cycling and driving through the study area with the, terraces were encountered and noted down. The transects were spread throughout the area as much as possible, so the fieldwork data could be used to make a covering terrace map.

4.2.3 Fieldwork

In total one and half months of fieldwork was done, most of it with my supervisor Ir. Wim Viveen. One week we were accompanied by Prof. Tom Veldkamp, Dr. Jeroen Schoorl and Dr. Ronald van Balen. During this week, the supervisors of my supervisor gave their view on the area.

Of the terrace levels and found exposures, the altitude and coordinates were noted. A description of the sediments that were found was made. The colour and texture of the soil were written down, just as the type, size, state of weathering, and roundness of the gravel. The height of exposures was measured and calculated as well.

Matrix colour was characterised with the colour scheme of by the Munsell Soil Colour Charts (Munsell, 1975). The texture was identified by experience since it is impossible to measure the size of a clay particle. In case of doubt, I used the triangle of the FAO-soil description guidebook (FAO, 1990). The type of rocks was determined with the use of a rock-classification book, and later on by experience. The maximum and average size of the rocks were measured and written down. State of weathering was estimated in three classes: Fresh rocks, moderately weathered rocks and weathered rocks. Fresh rocks can not be scratched and produce a loud high sound when hit with a geological hammer; moderately weathered rocks can be scratched and produce a sound when hit with geological hammer; and weathered rocks break easily when hit with a geological hammer and produce hardly any sound. The roundness was estimated by experience. In case the exposures were strongly concreted this was noted, just as the kind of concretion (clay, iron).
It was chosen not to use tools like the Schmidt Rock Test Hammer test for the amount of weathering (as for instance used by Blanco-Chao, 2002) or the Lüttig-method (Lüttig, 1962) for roundness, (as for instance used by Butzer in 1967). Because these methods would take up too much time in the field.

The height of the exposures was established by standing at a known distance (A) from the exposure and measuring the angle the clino-meter makes when looking at the top of the exposure. Using this angle, the eye height of the measurer and the distance toward the wall, the height can be calculated. In case hardrock or sapprolite was visible in the exposure, this is the base of the exposure. In figure 4.1 the formula is given and the method is explained with a small drawing.

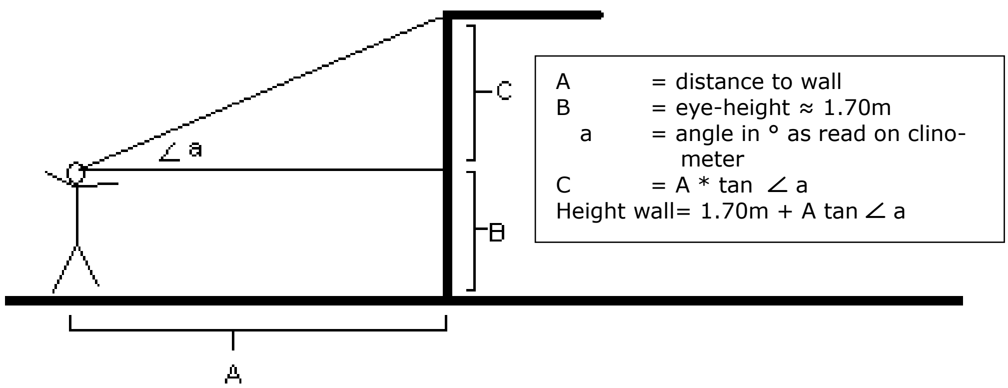

Figure 1: How the height of exposures has been established

A summary of data from a research of Viveen (2011, in progress) about composition, size, roundness and weathering of the rocks in three large gravel deposits in the O Rosal valley was used to supplement my data, when needed.

In case there were interesting features or structures in the colluvia- or gravel exposures, these were noted. A sketch was drawn and picture taken of the exposure. Sometimes the exposures show a clear flow direction or a dipping deposit, in these cases the directions were measured and written down as well. Often the exposures were covered with a layer of sand, plants, fungus or dirt. In order to get a clear view of the structures and the true composition of the soil, this was first removed. Unfortunately at the end of the fieldwork the camera broke down, so the last few days no pictures were made.

4.2.4 Data Processing

Digitising field data

All the notes which were made in the field were digitized and put in spreadsheets. This way a database was obtained with all the found field data. With use of the coordinates, this database was transformed to a point map which contains all the notes made at the visited locations. Using GIS-software, information from this map was combined with information of a DEM and aerial photographs, to make several maps. A terrace map, a map which distinguishes where which sediments were found, a map showing the imbrication of the large gravel deposits and a map showing the found tectonic tilt at two gravel deposits.

The imbrication was established was recognised from the larger flatter rocks, which have been deposited on top of each other as roofing tiles, and inclined to the flow direction ("*imbricate bedding*" 2011. Encyclopædia Britannica. Encyclopædia Britannica Online) as visualised in figure 2. Often this was hard to establish because always more directions could be found. In this case the direction was taken in which the majority of the larger gravels were pointing.

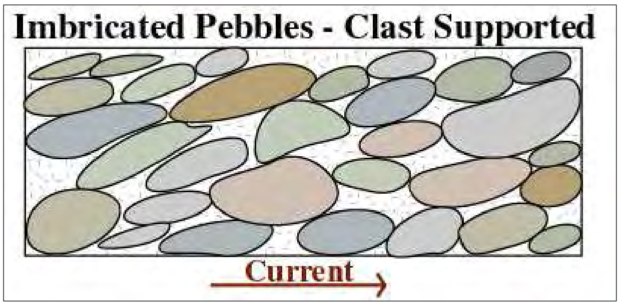

Figure 2: Imbricated gravels, current is from the left to the right
(source:http://www.umt.edu/geosciences/faculty/hendrix/g100/imbrication.jpg

Comparison of Terracelevels

Subsequently the found terraces have been put in tables and compared with the terraces that were found by other authors. The heights of the terraces in the O Rosal valley were compared with the height of the terraces along the coast. The corresponding terrace levels were compared to former sea levels of the last 800 ky and the rainfall data of the last 450 ky. With this comparison it was tried to get a better insight in the processes behind the formation of the terraces.

The precise identification of the terrace heights was a problem, since the terraces never are completely flat, it was difficult to find one single altitude per terrace. At first the different terraces were given their height in ranges, the highest to the lowest point. This was not a solution to the problem. The ranges in altitude made impossible to merge different terrace together to one terrace level. Therefore on the DEM the most continuous altitude within every terrace was identified, i.e. the altitude which occurred over the largest surface. Subsequently the terraces were categorised in terrace levels. The most reliable terrace levels were selected, based on the following criteria: total area of the terrace level; amount of terraces on that altitude; sediments found on the terraces; and land use (e.g built up area was thought to be less reliable than agricultural land). The terrace levels with a larger area, consisting of many different parts at the same altitude, containing sediment were believed to be most reliable.

The sea levels and rainfall data were found in literature and from personal communication with Sanchez-Goñi in Bordeaux. With use of articles and books on former climates, sea level change, tectonics and their influence on the landscape, the found information was put into context, and a reconstruction of the processes which formed the current landscape was made.

5. Results

In this part I show the results from the field work and the analysis of the available data. First I discuss the identified terrace levels and their sediment along the Spanish coast and compare them with literature, secondly I do the same for the Portuguese coast, and thirdly I discuss the O Rosal valley. In the fourth part all the terraces and sediments found on the different parts are compared. The fifth paragraph of this chapter compares the terrace levels with sea level and climate data, in the sixth paragraph a description of the big gravel deposits is given and in the last paragraph the general topography is discussed.

5.1 Spanish Coast

The Spanish coast is very steep. The mountains reach 450-500 meter mostly within 1500-2000 meter from the coast. Going further land inwards the slope decreases and altitude slowly rises up to 650 meter, also at an approximate 5000 meter from the coast (DEM). Here the results on this part of the study area are discussed.

5.1.1 Terraces along the Spanish Coast

Along the Spanish coast marine terraces are described from Oia down to the river mouth of the Miño river. In figure 3, on the next page, these terraces are visualised in a terrace map. At Oia and A Guarda more terraces are found close together, so these areas are enlarged a bit. For easier orientation the villages of Oia, Portecelo and A Guarda are mentioned in the map.

Eleven different terrace levels. A T1 (5-10 m), T2a (11-15 m), T2b (5-18 m), T3a (18-22 m), T3b (25-28 m), T4a (28-33 m), T4b (33-38 m), T5 (39-43 m), T6 (47-50 m), T7 (57-62 m) and a T8 at 62-67 m. The subdivision a/b is added, because these terraces lie in the same decametre above sea level.

The lower levels, T1, T2a and T2b are found in many places between Oia and the Miño, in terraces elongated along the coast. Levels T3a and T3b occur very little along the coast, only some small islands are present along the long stretched coast, with another occurrence at Oia, Portecelo and in A Guarda. The T4a, and T4b are especially found in Oia and A Guarda and both have only one occurrence along the coast. In both cases the terrace is the top of a platform sticking out from the mountain towards the sea. The T5 level lies at the altitude of the, almost perfectly flat, provincial road between A Guarda and Oia, with some larger areas north of A Guarda and in the village itself. The higher levels T6, T7 and T8 are only found in the village of A Guarda. A T6 lies up to the mountain slope of the Monte Torroso and T7 and T8 at the presumed ancient river passage of the Miño (Butzer, 1967). T7 is a terrace which connects to the Miño terraces in the east and marine terraces in the west, T8 is more or less an island on top of the T7-terrace. On top of the T8 is an old burg, which makes it hard to identify whether the surface is naturally flat.

It is clear that most levels are conserved at Oia and A Guarda. At A Guarda the whole sequence is found, except for T2a; at Oia only T2a and the levels above 40 meter are missing. Both locations are more probably more protected against powerful eroding waves because they are small inlets along a further completely straight coast. Waves probably already have lost a lot of energy before they reach these inlets, because they first encounter hardrock which lies in front of the coast. Therefore in the shelter of these inlets, terrace levels are preserved better.

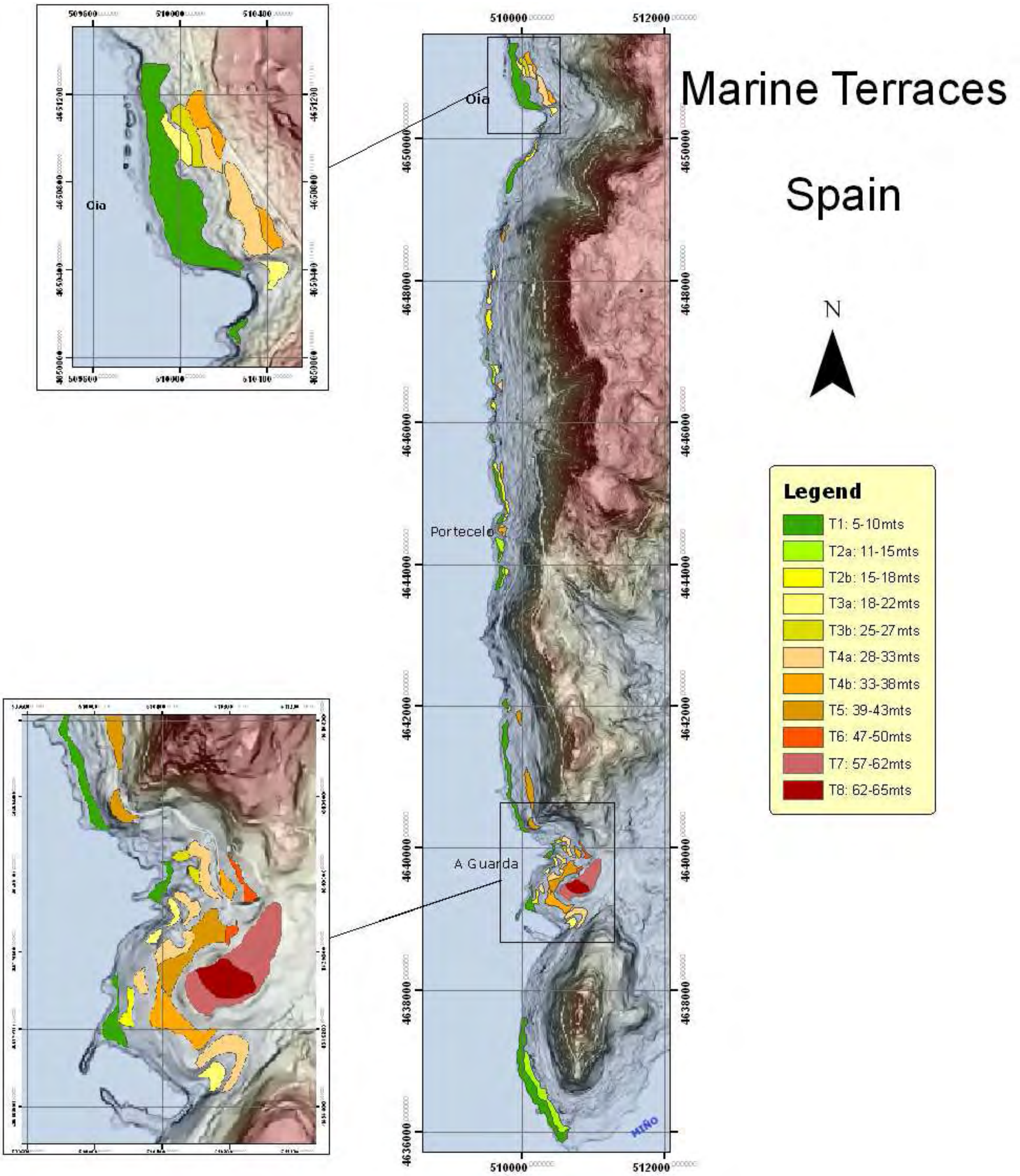

Figure 3: Marine Terraces Spanish coast

In table 1 the different terraces are mentioned with their altitude. Of the terrace levels, the different terraces are mentioned and the total area is calculated. Levels T1, T2a, T4a, T5 and T7 have the largest combined surfaces, all more than 10 ha. Terrace levels T4b, T3a and T2b occur less, and T3b, T8 and T6 hardly have smallest combined area. The terrace levels which occur the most, and have the largest surface are thought to be most reliable. Smaller terrace surfaces also imply shorter sea level high-stands (Hearty et al, 2007), though older terraces have possibly been eroded to some extent, changing the terrace size.

Table 1: Marine Terraces Spain

MARINE TERRACES SPAIN NUMBER	ALTITUDE (m.a.s.l.)	TERRACELEVEL	SUMMARY
3	5-7	T1	Range: 5 tot 7
51	7		AREA (m^2)
61	7		195.648
50	11-12	T2a	Range: 11 to 15
60	11-12		
29	12-13		
23	13-15		
25	14-15		AREA (m^2)
44	15		151.639
34	14-17	T2b	Range: 15 to 18
32	16-18		
45	17		
24	17.5-18.5		
17	17-18		
26	17-18		
31	17-18		AREA (m^2)
28	17-19		83.085
33	18-20	T3a	Range: 18-22
36	18-20		
58	18-20		
12	19-20		
30	19-20		
6	20-21		
14	20-21		AREA (m^2)
41	20-22		88.990
8	25	T3b	Range: 25-27
10	25		
20	26		
40	25-26		
59	25-26		AREA (m^2)
22	26-27		54.144
27	28-30	T4a	Range: 28-33
13	29-30		
11	30		
7	30-32		
38	30-33		
37	31-32		
4	32-33		AREA (m^2)
5	32-33		149.415
18	33-34	T4b	Range: 33-38
19	33-34		
35	33-35		
39	36		
52	36-37		
15	37-38		
16	37-38		AREA (m^2)
42	37-38		94.961
2	39-40	T5	Range: 39-43
21	39-40		
46	41-42		
43	41-43		
47	42-43		AREA (m^2)
56	42-43		127.077
57	47	T6	Range: 47-50
53	50		
54	50		AREA (m^2)
55	50		4.630
48	57-58	T7	Range: 57-62
49	60		AREA (m^2)
			108.286
1	63-65	T8	AREA (m^2)
			48.647

5.1.2 Marine sediment along the Spanish coast

Along the Spanish coast few sediments are found on marine terraces. The coast consists of granite cliffs, gravel beaches and locally sandy beaches in sheltered locations along the coast. The present gravel beaches consist of granite, quartzite, quartz or gneiss gravels. On the terraces, and sometimes in soils below the terrace levels, unweathered well rounded quartzite gravels are found from 8 up to 20 cm. In some exposures along the coast also rounded granite boulders are found (> 50 cm in size). Figure 4, on the next page, shows the areas where gravels have been found in this part of the study area.

Along the coast gravels are present on several T1 terraces. Gravel has only been found on higher levels at Oia and A Guarda. At Oia a T3a is present at 20 meter where well rounded quartzite are found. At A Guarda occasional gravel is found on top of a T4a, with a very thin soil on top of granite hardrock, and in a soil which forms the base of the 50 meter terrace. Interesting enough on lower levels gravel was not found in A Guarda. This can possibly be explained by the amount of construction which is going on.

Some interesting exposures are present along the coast. None of them show marine deposits, but they are shortly mentioned here for the completeness of the story.
At the base of terrace levels at Oia and Portecelo, exposures of around two meter high are found. It is recognised that sometimes the base of the terraces consist of dark brown silty sand, with around 5% of rocks. These rocks consist of broken angular quartz and broken angular granite flakes (ranging from a few mm to 5 cm), sometimes larger granite boulders, and an occasional quartzite gravel. The exposures show little structure and are probably slope deposits on top of the marine terrace. The occasional gravel in the exposure possibly comes from an older marine deposit.

At San Xiao about four interesting exposures are present just above the present beach. These exposures are up to eight meter high and more than eight different layers were identified. Well sorted stony layers are altered by badly sorted stony layers. Between these rocky layers also sandy or silty layers are found, often with small lenses of broken quartz of a few mm. The rocks consist of quartz and granite. The quartz range from a few mm to 5 cm and are angular to sub angular; the granite range from scrapes of a few centimetres to blocks of a meter in diameter and range from angular to rounded.

The different layers on top of each other, with coarse and chaotic layers altered by fine and sorted layers, represent depositional events with a lot of energy and events with less energy. Most probably these events are caused by changes in discharge coming from the hill, due to changes in climate. These are certainly not marine sediments. There are clearly distinguishable layers and the rocks are often still angular. Quartzite are not present in the exposures, which are present on the older terraces and on the present beach. These deposits are slope deposits. For further reading: Blanco Chao et al. (2003) did research on these deposits.

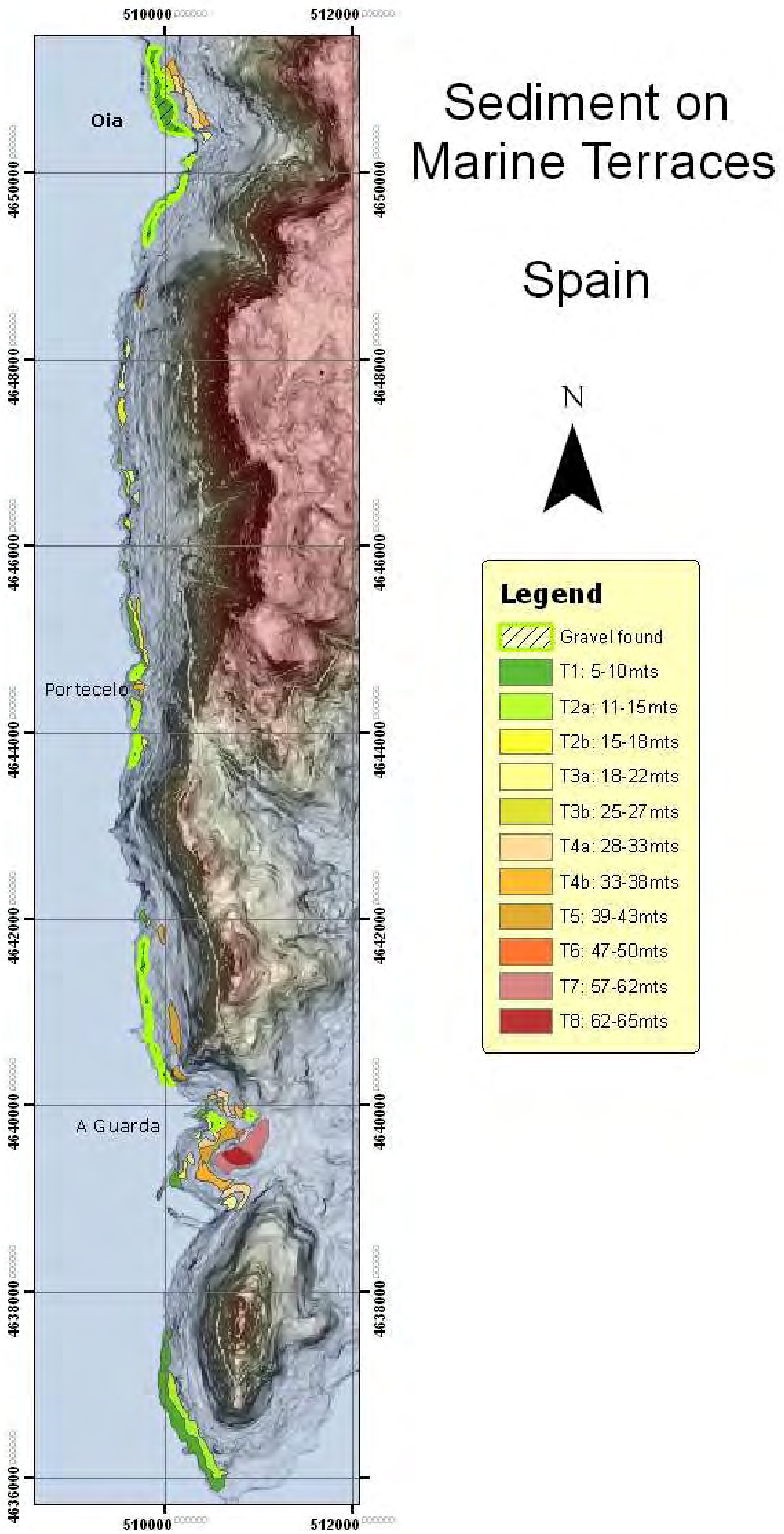

Figure 4: Gravel found on marine terraces in Spain

5.1.3 Comparison of marine terrace levels with literature

Butzer finds different levels in A Guarda. At 5 meter, 11-12 meter, 17,5 meter, 36 meter and 45-48 meter. At all these altitudes I also find terrace levels, the altitudes correspond with my T1, T2a, T3a, T4b and T5. In Portecelo he finds levels at 6 meter, 15-17 meter and 35-36 meter. The lowest level is not present, but the 15-17 meter terrace corresponds with the T2b and the highest terrace could be the same as the level I find at 33 meter. Apart from these specific terrace levels, he also mentions some general terrace levels (2.5 m, 7-8 m, 10-11 m, 23-24 m, 33-36 m, 44-49 m). Apart from the 2.5 m and 23-24 m terraces, this also corresponds well with my results.

Cano Pan et al. (1997) only visualise terraces in A Guarda on their map. They find a T2 around the southern point of the base of the Sta. Tegra between 10-19 meter; a T4 between 32 and 40 meter stretching North-South, west of the presumed ancient river passage of the Miño; a T5 level 42-53 meter up to mount Torroso and in the middle of the former river channel a T6 level at 67-72 meter. All levels have been found. However the T2 is smaller than drawn by Cano Pan et al., the northern part is too steep for terraces and the terraces facing the Miño are covered by dunes. The T4 is found as a T4b and T5 in my classification; of the T5 I find only very small elongated parts (T6 in my classification). The highest level has also been found, though somewhat lower at 62-65 meter.

When the found marine terraces on the Spanish side are compared with the ones which have been recognised on the geological maps of Oia and La Guardia (1:50.000) it is noticed that the classification on the geological maps is more conservative than mine. Pliego Dones and Corretge (1978) have only found low terraces, and at fewer locations than I have, possibly due to the scale of their map. They found a marine terrace in Oia between 0-10 meter, which corresponds with the T1 I found there at 5-10m. However, I have found convincing marine levels at 38 meter, which the authors identify as colluvium. Further south the map of La Guardia of Abril Hurtado and Corretge (1978) shows the same trend. They find few terraces, and practically the whole part is identified as colluvium. They identify only two low terraces (up to 10 meter), one around 1000 meter south of Oia and one 2300 meter north of Portecelo. The terrace south of Oia is confirmed by me. The terrace north of Portocelo is only very small and one of the least convincing ones I found, because of poor flatness. The total area at A Guarda is described as colluvium, and one of the most convincing T1's I found just north of A Guarda is ignored. On the next page table 2 is shown in which a small summary is given of the comparison with the found terrace levels by Butzer (1967) and Cano Pan et al. (1997) and the geological maps by Pliego Dones and Corretge (1978) and Abril Hurtado and Corretge (1978).

I have found more terrace levels than the other authors, but most of the terrace I find correspond with theirs. Sometimes they find a slightly different altitude for the terraces; or they use large intervals which sometimes cover two of my intervals. It is nice that Butzer (1967) uses very small height intervals, however he does not show a terrace map, which makes comparing his results with mine difficult because the exact location is not known. How he comes up with terrace levels at 2.5 meter is unclear however, since at this height normally still a beach is present.

Cano Pan et al. (1997) show a nice terrace map in their article. Some levels agree with my results, but they also identify levels where the slopes are very steep. And fail to mention the next highest level at the former Miño river passage. Personally I think this terrace at 57-62 m is better preserved than the top level, it runs from the Miño valley to the sea front and is very flat.

The geological maps only show T1 terraces along the coast, and even in the identifications of the T1 terrace they are very conservative, ignoring many convincing levels with gravels found.

Table 2: Comparison of different terrace levels along the Spanish coast

Comparison Marine Terraces Spain with literature				
	Butzer (1967)	**Cano Pan et al. (1997)**	**Pliego Dones & Corretge (1978)**	**Corresponding level this research**
General	T1a (2.5 m)			noot found
	T1b (7-8 m)			T1 (7-8 m)
	T2 (10-11 m)			T2a (11-12 m)
	T3 (23-24 m)			not found
	T4 (33-36 m)			T4b (33-36 m)
	T5 (44-49 m)			not found
A Guarda & Sta. Tegra	5 m			T1
	11-12 m			T2a (11-12 m)
	17.5 m	T2 (10-19 m) Up to the point at the Sta Tegra, and around it		T2a (18 m), though not around the point.
	36 m	T4 (32-43 m) stretching N-S		T4b (33-36 m) and T5 (39-40 m)
	45-50m	T5 (42-55 m) North of the old river channel		T6 (47-50 m)
	45-48m			T6 (48 m)
		T7 (65-72 m) top of old river channel		T8 (62-65 m)
Portecelo	6 m			T1 (7-9 m)
	16 m			T2b (16-17 m)
	35/36 m			T4b (33 m)
Portecelo - 2300m N			0-10mts	T1 (5-7 m) Not very convincing
Oia			0-10mts	T1 (5-7 m)
Oia -1000m S			0-10mts	T1 (5-7 m).

5.1.4 Discussion

Very few terraces are present along the Spanish coast. The slopes are probably too steep to be able to conserve nice big flat terraces. At the villages Oia and A Guarda most terrace levels have been found. On one hand this is dangerous because people tend to make their close environment as flat as possible, on the other hand both villages are built in depressions along the coast which gives more room for the preservation of the marine terraces.

It is clear that the Spanish part of the coast is very hard to interpret. but I find the geological maps issued by the ministry of industry and energy too conservative. It is true that large parts of the coast are covered by colluvium, and beautiful ancient beach deposits are not found. However, at quite a few places convincing flat stretches are present which are sloping towards the sea, and often marine gravels lying around the surface.
In most instances I do agree with the results of Butzer (1967), although our results differ in identification of the altitude, probably because nowadays more detailed altitude data is available. Cano Pan et al. (1997) I find sometimes a bit enthusiastic in his drawing up of the terraces, but in broad lines the results correspond. I think my results are a good addition and refining to the work Butzer (1967) and Cano Pan et al. (1997) did.

The most convincing levels found in the study area according to their size and occurrence lie probably at T1 (5-10 m), T2a (11-15 m), T4a (28-33 m), T5 (39-43 m) and T7 (57-62 m). The T2b and T3a levels are harder to identify because total surface areas are not as big as the T1/T2a, but still flattened for agriculture. Possibly these levels are overlain by colluvia. In general, the areas above the 30 meter do not have this problem, because they are either too steep, or convincingly flat. On levels T1, T2a, T3a gravel is present in large quantities. On T4a (28-33 m) and T6 (47-50 m) these are found on occasion. Agreement with other authors exist on the levels on T1, T2a, T2b, T4b, T5, T6 and T8. Combining this information the most reliable levels are T1 (5-7m), T2a (11-15m), T2b (15-18 m), T4a (28-33 m), T4b (33-38 m), T5 (39-43 m), T6 (47-50 m), T7 (57-62 m) and a T8 at 62-67 m.

5.1.5 Conclusion

Eight different terrace levels are identified with three different sublevels. T1, T2a, T2b, T3a, T3b, T4a, T4b, T5, T6, T7 and T8. Of these levels T1, T2a, T2b, T3a, T4a, T5, T6, T7 and T8 are the most reliable. The terrace levels correspond well with what the other authors wrote, although slight differences in interpretation of height or the extent are made. Occasional gravel is found up to T6, larger quantities up to T3a. Some exposures are present of slope deposits but ancient beach deposit are not found in the area.

5.2 Portuguese Coast

5.2.1 Marine terraces along the Portuguese coast

Along the Portuguese coast marine terraces are described from Caminha down to Viano do Castelo. The terraces are visualised in a terrace map which can be seen in figure 5. Table 3 shows all the found terraces, their altitude, and their size. Terraces levels range from 5 meter to 105 meter in altitude and can be subdivided into ten different levels, with six sublevels. A T1 (5-10 m), T2a (10-13 m), T2b (14-17 m), T3a (20-25 m), T3b (25-28 m), T4a (28-33 m), T4b (33-36 m), T5a (38-41 m), T5b (44-48 m), T6a (48-52m), T6b (55-56 m, T7a (58-62 m), T7b (62-65 m), T8 (70 m), T9 (77-80 m) and a T10 (95-105 m). Especially the lower levels T1, T2a, T2b and T3a are almost continuous. Except for Montedor, where only a T2a is found.

Also the middle terrace levels (T3b-T6a) occur at many places. At Moledo all middle levels can be found. At 25-28 meter, 28-33 meter, 33-36 meter, 38-41 meter, 44-48 meter, and 48-52 meter. Unfortunately the whole area is built up, so sediments are not visible. A little further south, north of Vila Praia de Âncora a T4a and T4b can be found stretched along the mountain slope. On an out sticking piece of rock remnants of a T3b can be found. An elongated T5b is found just SW of the large quarry, which can be recognised by the white spot on figure 5 on the next page. South of Vila Praia de Âncora some larger terraces are found, at 28-33 meter and 38-41 meter continuing into the valley at Afife. South of Afife a T4a, T5b and T6a are found. Another T6a is found at Montedor. Moving further towards Viano do Castelo some elongated T3b, T5b and T6a levels are present against the mountain slope.

Higher levels are well preserved in Moledo. The high levels T6b, T7a, T7b, T8 and T9 can be found, making sure that from 5 meter up to 80 meter every terrace level is represented. South of Afife high levels are found in the forest, one at 62-65 meter and another at 95-105 meter. It should be noted that these higher levels (from T6b upwards) do not occur often, and are mostly (all, except for a small T7) found on only one location, nor any gravels have been found. So it is possible that these are man-made terraces; coincidentally colluvia have been deposited flat; or they are flat due to a different kind of lithology.

The black parts on the map are areas which have another origin than marine. The flat part east of the 55-56 meter terrace at Moledo is probably formed by a small creek which has incised between the terrace and the mountain to the east. It is not sloping towards the sea, but is terraced in many small steps towards the north. Another peculiar part is found at Afife where a flat level is found on top of a hill at 69 meter. This hill slopes towards the east, and has an almost vertical wall towards the sea. This makes it unlikely that the level is of marine origin. East of Afife an isolated flat area is found between 100 and 150 meter, with a slope around 8%. At Montedor a large hill of 75 meter high is found at a distance to the sea where normally T1, T2a or T2b terraces lie. This hill is sloping in all directions and does not have nicely flat stretches. However at the back of the hill some terrace levels are found.

In table 3 can be seen that the T1, T2b, T3a are most prominent levels of the lower terraces; and T4a, T5a and T6a the most prominent of the middle terraces. The higher levels do not occur often and only cover a small area.

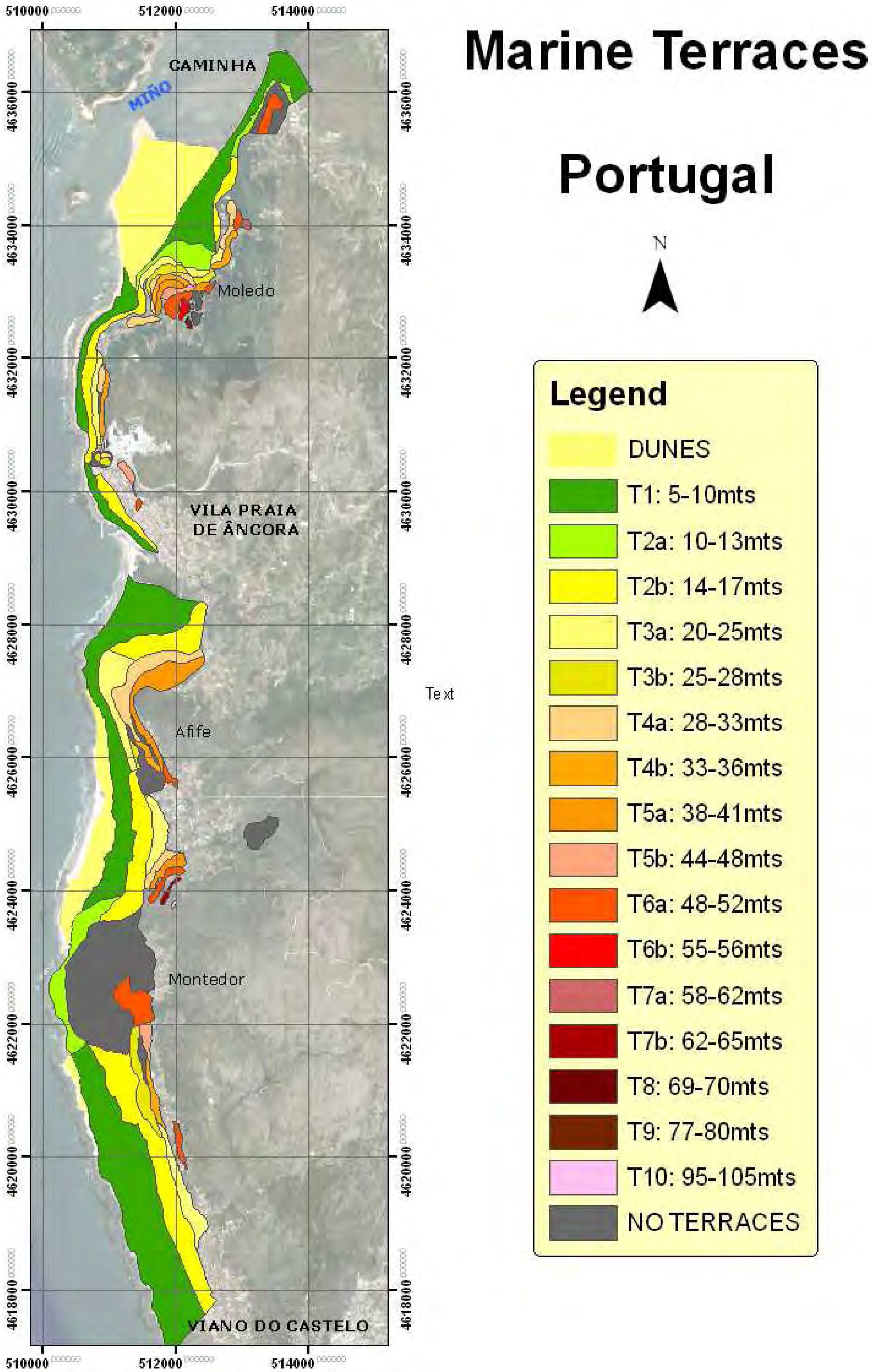

Figure 5: Marine Terraces Portugal

Table 3: Terraces along the Portuguese coast

MARINE TERRACES PORTUGAL			
NUMBER	**ALTITUDE (m.a.s.l)**	**TERRACE LEVEL**	**SUMMARY**
235	5-7	T1a	Range: 5-10m
110	5-7	T1a	
143	6-9	T1a	
146	6-9	T1a	
23	7-9	T1a	
2	7-10	T1a	
5	7-10	T1a	
37	7-10	T1a	
48	7-10	T1a	
99	7-10	T1a	
112	7-10	T1a	
197	7-10	T1a	AREA (m^2):
118	7-11	T1a	6.141.006
12	10-13	T2	Range: 10-13m
128	10-13	T2	
113	11-13	T2	AREA (m^2):
114	11-13	T2	855.867
196	12-17	T2b	Range: 14-17m
62	13-16	T2b	
41	14-15	T2b	
119	14-17	T2b	
242	14-18	T2b	
166	14-19	T2b	
161	15-16	T2b	
16	15-17	T2b	
248	15-17	T2b	
145	15-17	T2b	AREA (m^2):
51	15-20	T2b	3.013.654
249	20-21	T3a	Range: 20-25m
97	20-21	T3a	
147	20-23	T3a	
127	20-24	T3a	
58	22-24	T3a	
208	22-25	T3a	AREA (m^2):
107	22-26	T3a	1.109.098
96	24-25	T3b	Range: 25-28m
170	24-28	T3b	
44	25-28	T3b	
52	25-28	T3b	
81	25-28	T3b	
134	26-27	T3b	AREA (m^2):
135	26-27	T3b	403.028
45	28-30	T4a	Range: 28-33m
25	28-33	T4a	
210	28-33	T4a	
254	30	T4a	
86	30-31	T4a	
159	30-32	T4a	
250	30-33	T4a	
252	30-33	T4a	
120	30-34	T4a	
187	30-34	T4a	AREA (m^2):
54	31-33	T4a	683.390
121	32-40	T4b	Range: 33-36m
18	33-36	T4b	
40	33-36	T4b	
57	33-36	T4b	
82	33-36	T4b	
55	35-36	T4b	AREA (m^2):
94	35-36	T4b	346.190
29	38-40	T5a	Range: 38-41m
43	38-40	T5a	
207	38-42	T5a	
92	40	T5a	
251	40-41	T5a	AREA (m^2):
202	40-44	T5a	564.118
186	42-45	T5b	Range: 44-48m
17	44-47	T5b	
91	44-47	T5b	AREA (m^2):
46	45-48	T5b	483.389
116	45-50	T6a	Range: 48-52m
47	47-48	T6a	
19	47-49	T6a	
218	48-50	T6a	
219	48-52	T6a	
137	48-52	T6a	
130	49-52	T6a	
35	50	T6a	
26	50-53	T6a	
204	50-53	T6a	AREA (m^2):
199	52-55	T6a	635.863
34	55-56	T6b	Range: 55-56m
			AREA (m^2): 33.131
122	58-62	T7a	Range: 58-62m
33	60	T7a	AREA (m^2): 23.926
27	62-65	T7b	Range: 62-65m
205	62-65	T7b	AREA (m^2): 27.174
32	70	T8	Range: ± 70m
			AREA (m^2): 4.717
31	77-80	T9	Range: 77-80m
			AREA (m^2): 6.838
28	95-105	T10	Range: 95-105m
			AREA (m^2): 4.848

5.2.2 Deposits along the Portuguese coast

Along the whole Portuguese coast gravels are found on the lower marine levels. At the beach these gravels consist of granite, quartzite, quartz and gneiss. On the T1 and T2a levels well rounded granite and quartzite lie, but on the higher levels only quartzite remain. This is more or less in correspondence with what Texier and Meireles found (2000). Although they also mention occurrence of gneiss on the low terraces and quartz on the higher terraces.

Figure 6 shows the terrace levels which contain gravels. Apart from built up areas, T1, T2a, T2b always contain gravel. At a few places gravel is also found at higher altitudes. T3a
South of Moledo and northwest of Afife the whole terrace sequence contains gravel up to T5a (38-41 m).

Two nice corresponding terrace sequences lie south of Moledo and north of Afife. A T1, T2b, T3a, T4a and T5a are found at both locations. All of them contain gravel. The higher levels south of Afife are built up, so gravels are not found here. Although some occasional gravels are present in the forest, at a T6a. This level also occurs at Montedor, Moledo, Christelo and Caminha. At Montedor, and apparently at Moledo (Teixeira, 1952) also gravel deposits are found.

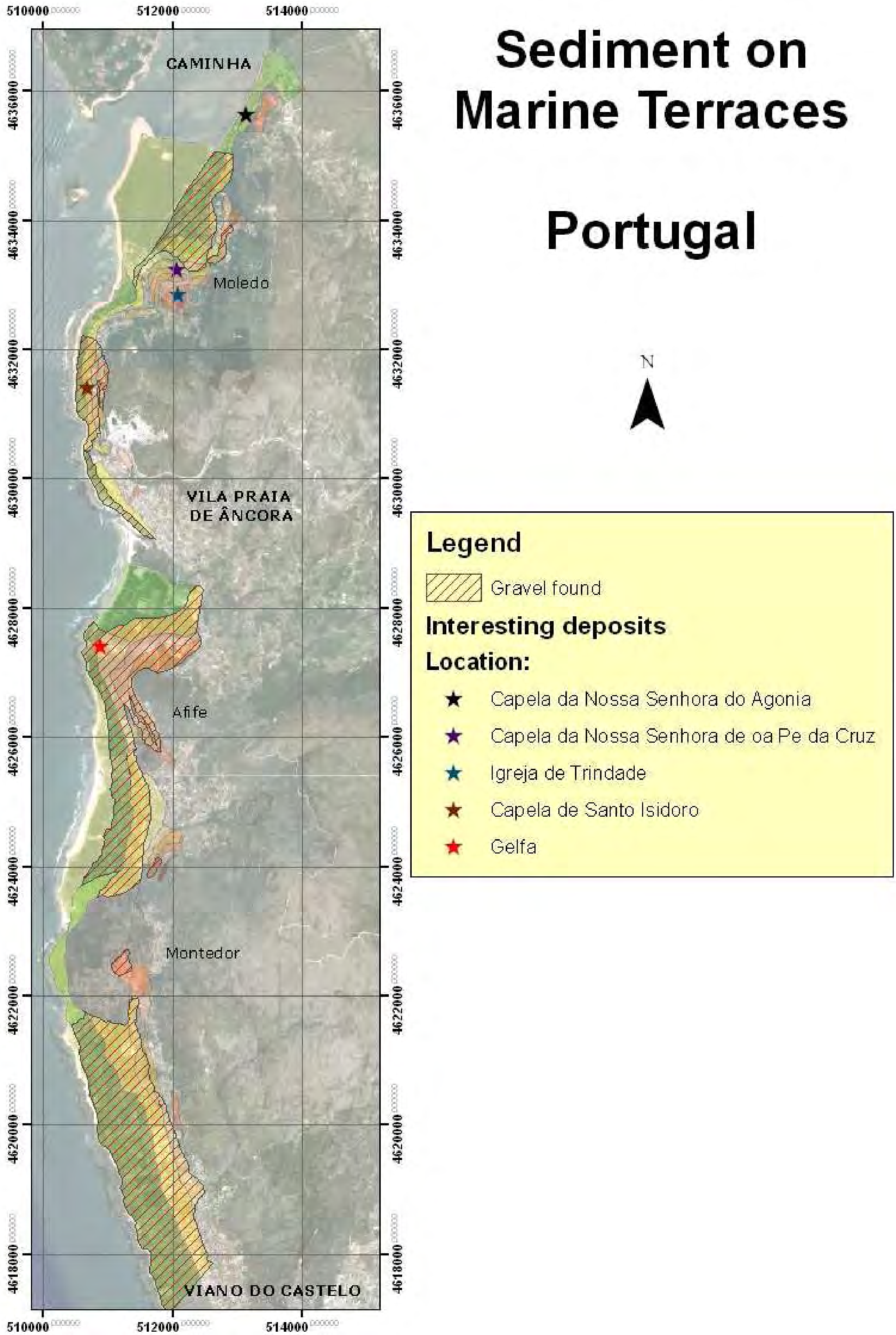

Figure 6: Sediments found on marine terraces

The most interesting gravel exposures along the Portuguese coast.

I shortly discuss three interesting deposits along the Portuguese coast. Figure 6 shows five stars, which represent interesting gravel deposits found by me or by Teixera (1952). The three most northern deposits have not been confirmed by me, as will be discussed in the next chapter.

- Chapel of Santo Isidoro
The fourth star from the north is the chapel of Santo Isidoro. At this chapel an exposure of one to two meter has been found at an altitude of 17 meter, in the excavation of the railroad. The exposure shows well rounded unweathered quartz, quartzite, granite and gneiss up to 25 cm in size in a yellow clayey matrix. As can be seen in figure 7. These gravels are overlain by a large granite block with rounded edges of 3.5 m x 1 m. On the sides of the exposure brown soil is found up to 2.5 meter high, full with gravels, broken blocks of granite up to a meter in diameter, and rounded granite boulders.

Discussion
This deposit has been described by Teixeira (1952) as well. The gravels are similar to the gravels found on the beach, and lie underneath a large block of granite which offers a protected environment for conservation. This part of the exposure is clean and the top is a convincing terraces level. This favours the idea that the gravels are possibly still in its original place, and it is an ancient marine beach deposit. On the other hand it is unsure how much the deposit has been altered by construction of the rail road. The exposures on the sides are messy with dark soil and angular granite blocks in it which implies that the construction of the railroad probably was quite devastating. The exposure +/- 930 meter south of the chapel shows that large parts have probably been blown up. So at best it is probably a human altered marine beach deposit.

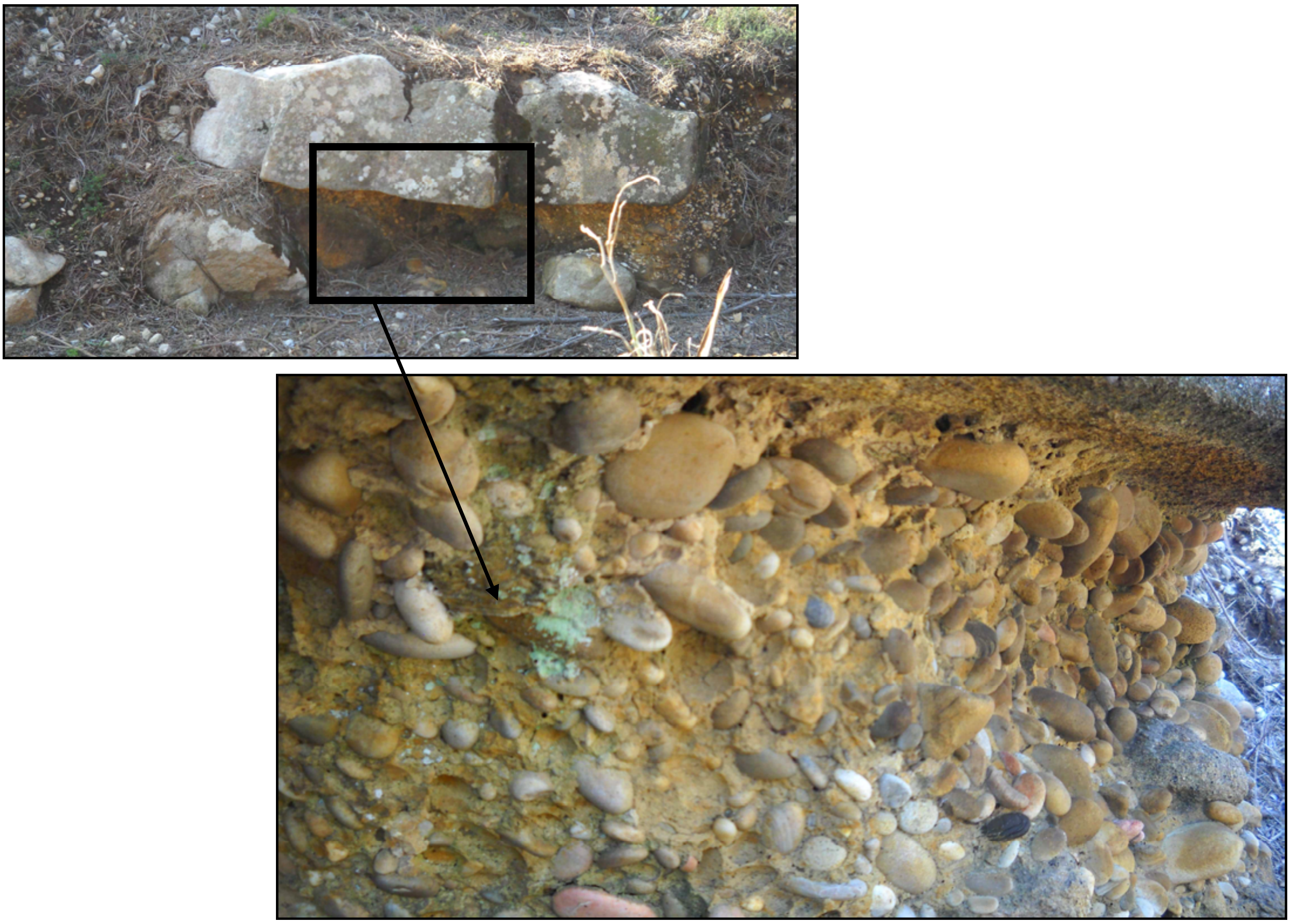

Figure 7: Gravel exposure below a T2b at chapel Santo Isidoro

- Blown up Deposit
A little bit further south, west of the large quarry north of Vila Praia de Âncora, between the railroad and the sea, exposures have been found on top of granite hardrock and in its alcoves. On top of the granite hard rock, gravels lie in a dark soil of 150 cm high, surrounded by subrounded granite blocks. In the alcoves of the granite hard rock are small exposures of 20-40 cm, consisting of granite and quartzite gravels in an oxidised cemented matrix.

The surface is not flat at the moment, a few granite blocks stand in the landscape between small lakes and lower parts. Most probably at first it was a flat level and later blown up, possibly during the construction of the railroad. Figure 8a shows the mildly sloping granite hardrock (5-7% towards the sea) covered by granite blocks and gravels in a dark matrix, and the possible excavation or demolishing of the terrace. Figure 8b shows a gravel deposit in one of the alcoves of the granite hard rock.

Discussion
These exposures face the same problems as the exposure at Capelo de Santo Isidoro. The fact that some gravels lie in a cemented matrix with oxidation marks in alcoves of granite hard rock point to an in situ deposit. The possibility that most of the hardrock has possibly been blown up and the messy deposits on top of the hard rock make it less obvious. This favours the idea of either a colluvium or a human deposition.

Figure 8a: Overview of the possibly blown up exposure at Vila Praia de Ancora

Figure 8b: A deposit in one of the alcoves of the granite

- Gelfa

Figure 9: Gravel exposure at Gelfa showing well rounded gravels. Sea lies to the right.

The most southern star on the map in figure 6. is a gravel exposure at Gelfa. This is a gravel pack with a depth of more than two meter, covering an area of at least 100 x 150 meter. Similar gravels have been found up to the rail road 400 meter to the west, but these could be moved.
The gravels have an average size of 8 cm up to a maximum size of 25cm. The exposure shows well sorted layers of smaller gravels and bigger gravels, as well as sand layers. The rocks consist of perfectly rounded unweathered quartzite (90%) and quartz (10%), really hard to break (in total +/- 40 rocks). Although the terrace is sloping towards the sea it has a very similar structure to the fluvial terraces found along the Miño. The exposure is situated 1,3 km south of the present estuary of the Rio de Âncora, which makes it a possible fluvial terrace. However the Rio de Âncora does not have quartzite in its basin.

Discussion
It is a peculiar exposure. It has clear marks of a fluvial terrace (sandy layers, well sorted layers with gravels of different sizes, extent, imbrication) however the transition to the marine terraces at the same height is very gradual. The gravels are very fresh, perfectly rounded and consist almost completely of quartzite, just like the gravels found on the marine terraces. Granite gravels are not found, which occasionally still occur on marine terraces between 14-17 meter.
If it is a fluvial terrace it is unclear where the gravel can come from since the closest source of quartzite is the Miño river according to the geological maps of the area. It seems illogical that a river with an estimated average discharge +/- 2m3/s could deposit > 30.000 m3 of gravel.

5.2.3 Comparison of the marine terraces along the Portuguese coast

Here I discuss the terrace levels found by former researchers who have been working on the Portuguese coastal terraces. Results of the work of Texier and Meireles (2000), Butzer (1967), Teixeira (1952) and this research are compared. In table 4 the different terrace levels are shown in a way that it is clear which levels correspond with each other.

Texier and Meireles (2000) found ten different terrace levels along the Portuguese coast, with a range of 3-140 meter. They put their results in a terrace map, which is comparable to mine. Texier and Meireles (2000) found most levels in the valley at Afife (Rio de Cabanas) and the valley at Vila Praia de Ancôra (Rio de Ancôra), these two valleys I skipped in my research to prevent possible interference from fluvial terraces formed by the small rivers. At other places also high terraces are found. But unfortunately they do not give a height indication on their terrace map, so it is hard to conclude whether our results contradict or correspond. Unfortunately, as can be seen from table 4 the subdivision we made of the terrace heights differs. They found terraces at altitudes I did not find any. For example at 3-5 meter or 18-22 meter.

The general trend of the map is the same. Two continuous low terraces up to 20 m; levels at Moledo; terraces north of Vila Praia de Ancora, SW of the quarry; hill at Montedor,; are all identified and drawn similarly. The highest level they mention in the study area lies at 48-54 meter, the same altitude at which I find gravels. In this case my results confirm the findings of Texier and Meireles (2000).

Teixeira (1952) describes a few locations where gravel deposits of old beaches are present between Caminha and Vila Praia de Âncora. The deposits are shortly mentioned from north to south.
The first deposit is situated in Caminha above the church Senhora da Agonia at 50-52 meter. The second lies on the northern edge of village Moledo at Capela de Nossa Senhora de ao Pe da Cruz at 30-35 meter. In the middle of Moledo at Capela or Igreja de Trindade at 50-52 meter a level is found, and two levels are described at Capela de Santo Isidoro, at 5-6 meter and 15-20 meter. The locations are visualised in figure 6 to make an easier comparison with my own observations.
All the levels Teixeira (1952) describes are confirmed by me. However, neither at Caminha, nor at Moledo gravel deposits are found. Only at the low levels T1 and T2b at the chapel of Santo Isidoro indeed gravel is found as described in paragraph 5.2.2 (fig. 6). Since the work of Teixeira is over half a century old, it is possible ‘recent’ construction in the area has made the villages less accessible, and the deposits less visible.

Table 4: Comparison of terrace height with literature, Portuguese Coast			
Terrace levels found by different authors along the Portuguese coast			
Texier& Meireles (2000)	**Buzter (1967)**	**Teixeira (1952)**	**Corresponding terrace this research**
M10: 3-5 m	T1a: 2.5 m	5-6 m	T1: 5-10 m
M9: 8-14 m	T1b: 7-8 m		
	T2: 10-11 m		T2a: 10-13 m
M8: 18-22 m		15-20 m	T2b: 14-17 m
	T3: 23-24 m	15-20 m	T3a: 20-25 m
M7: 25-27 m			T3b: 25-28 m
M6: 31-36 m	T4: 33-36 m	30-35 m	T4a: 28-33 m / T4b: 33-36 m
M5: 41-45 m			T5a: 38-41 m
M4: 48-54 m	T5: 44-49 m	48-52 m	T6a: 48-52 m
M3: 63-67 m			T7b: 62-65 m
M2: 80-88 m			T9: 80 m
M1: 100-140 m			Flat found east of Afife (?)

Butzer (1967) only mentions general levels at which marine terraces occur. Except for the T1 terrace at 2.5 meter most levels correspond well. My T1 corresponds with his T1b, my T2a to his T2, my T3a to his T3, my T4b to his T4 and my T6a to his T5. The 2.5 meter level does not exist in the study area. But the T1b, T2, T3 and T4 and T5 do indeed occur often.

Even though these researches (Teixeira, 1952; Butzer, 1967; Texier and Meireles, 2000; and this research) differ a little bit in the altitude ranges of the terraces are subdivided, and at which altitudes they are found, the trend and location at which terrace levels of this research, corresponds well with earlier work. It is interesting to see that all authors agree that the highest terrace lies around 50 meter. This research describes levels up at 60 meter in Christelos; up to 80 meter in Moledo; and at 62-65 m and 95-105 m south of Afife. It is impossible to prove a marine origin of the terraces due to lack of sediment. The levels at Moledos are very flat, but all covered by houses or concrete and can be partly be terraced by humans. The levels at Afife are in a forest which makes the identification difficult due to trees and wobbly surface.

5.2.4 Discussion and Conclusion

Many terrace levels are identified. Levels T1 (5-10 m), T2b (14-17 m), T3a (20-25 m), T3b (25-28 m), T4a (28-33 m), T5a (38-41 m) and T6a (48-52 m) are the most convincing looking at their size, occurrence in the landscape and at the occurrence of gravel. The trend and location of the terraces correspond well with what other authors find, although sometimes the altitudes differ. This can however be blamed on the measuring device or the source of the altitude, as will be shown in paragraph 5.3.3.
The other terraces are T2a (10-13 m), T4b (33-36 m), T5b (44-48 m), T6b (55-56 m), T7a (58-62 m), T7b (62-65 m), T8 (70 m), T9 (77-80 m). The lower levels T2a and T4b and the southern T5b possibly differ in height due to colluvium lying on top. T5b also occurs in Moledo, just as T6b, T7a, T7b, T8 and T9 and these higher levels can neither be confirmed not refuted since they in built up area and do not contain gravel. As there is not another occurring terrace on the same altitude, the possibility exists these terraces are man-made.

Gravel consists of granite, quartzite, quartz and gneiss, however above T2 only quartzite gravels can be found, which shows that this is the most resistant rock (Repka et al.,1997). None of the three gravel deposits is a convincingly intact ancient marine terrace. The two most northern deposits (chapel de Santo Isidoro and north of Vila Praia de ÂNora) are possibly marine deposits which have been altered during the construction of the railroad. The exposure at Gelfa is most probably a river terrace. It has many fluvial characteristics and structures; the composition is different than gravels found on marine terraces of the similar height, and it lies close to a small river. However it is uncertain where the quartzite come from since these can not be found in the catchment of the Rio de Ancora.

5.3 O Rosal valley

The O Rosal valley can broadly be subdivided in five different parts. First part is part I; a big block of terraces going up to the north, in the middle of the O Rosal valley. Part II is the area of As Medas and O Rosal with low flats in between. Part III is the lower Tamuxe river, from the end of the gorge to the joining with the river Miño. Part IV is upper Tamuxe river. The fifth part forms the terrace levels found by A Guarda and along the Sta. Tegra. In Figure 10 A small map is shown, showing these different parts of the O Rosal valley.

5.3.1 Terrace levels in the O Rosal valley.

Figure 10 shows that all the terraces in PART I are running in a NE-SW direction. More or less parallel to the current Miño river channel. The top of PART I lies in the north and west at 50 meter, at A Cunchada.
In PART II there is a large low stretch which separates the 50 meter terrace at A Cunchada with the 50 meter terrace at As Medas, and O Rosal. In between however is still a terrace level at 40 meter, on both the north and south side of the low stretch. These terraces are having their terrace scarps more or less parallel to the little creek flowing in the lower stretch.
The Tamuxe river flows out of a very small gorge into PART III. At the entrance of PART III the valley in which the Tamuxe flows abruptly becomes a lot wider. Part III looks like a valley within a valley. A small sub-valley in which the Tamuxe has incised itself, in the larger O Rosal valley. It is interesting to see that the Tamuxe river flows very to the east of its little sub valley. The terraces found in Part IV and III all have their terrace scarps parallel to the Tamuxe.

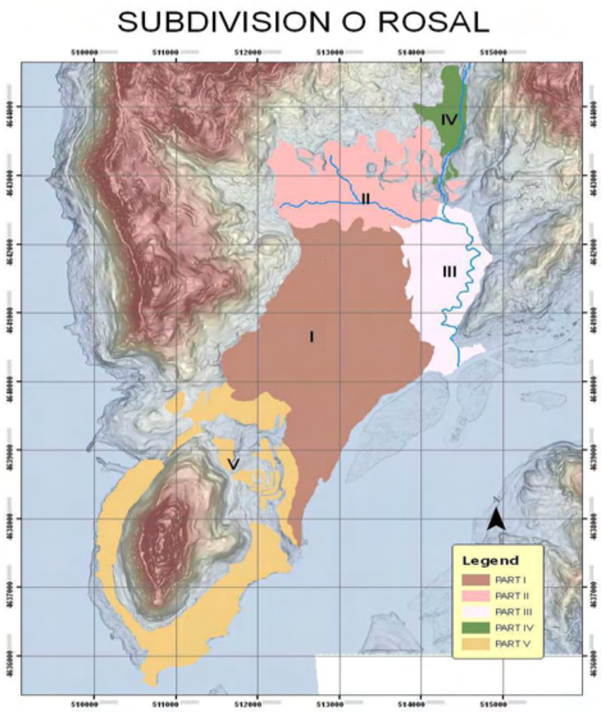

Figure 10 : Subdivision of the terraces in the O Rosal valley

The terraces found in part V are smaller, and more sub steps are found, especially in A Guarda. These terraces have their scarps towards the east or south, more or less parallel to the Miño.

Information obtained from transects and different maps is used to make a map of the terraces in the O Rosal valley. The found terraces, their levels and their height have been measured in relation to the Miño river, which runs at sea level in the study area. Only the terraces in the upper Tamuxe river, part IV in figure 10, are given their levels and heights in relation to the river level of the Tamuxe river. The terraces found in the flat lower part of the Tamuxe river (part III in figure 10 are probably also formed by the Tamuxe river, however the Miño has been used as reference level because the lower part of the Tamuxe river does not have a lot of gradient. In the north-western part (II) of the Rosal valley upper terraces at 40 and 50 meter are probably formed by the river Miño, while the lower terraces are possibly remnants from an incision of the side creeks of the Tamuxe. For more clarity the lower levels have been given their height in relation to the Miño. This map can be seen in figure 11.

Thirteen different terrace levels can be identified. Ranging from 4-5 meter at the Miño, to 59-62 meter at the separation between the marine front in A Guarda and the Miño valley. Most terrace levels have a range of around 3 meter.

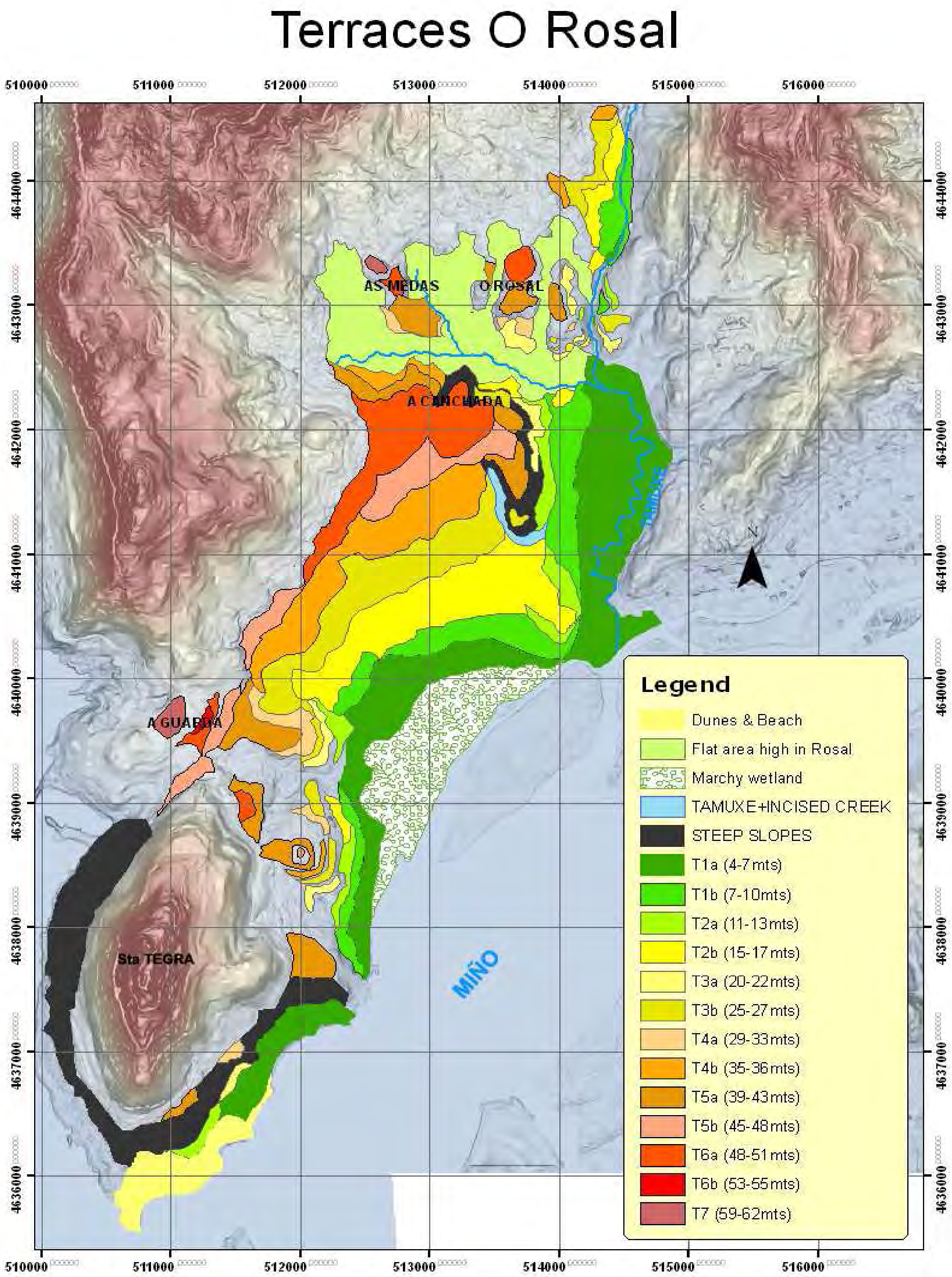

Figure 11 : All found terraces in the O Rosal valley

Moving to the north from the Miño, first wetland is encountered with an altitude of around one meter above sea level. Subsequently level T1a (4-7 m) and/ or T1b (8-10 m) is found, followed by a T2b (15-17 m); T3b (25-27 m); T4b (35-36 m); T5a (39-43 m); and T5b (45-49 m) at A Cunchada. Directly north of A Cunchada in part V there are two lower terraces levels: T5a (39-43 m) and T4b (36-35 m) to the west and T3b (25-27 m), T2b (15-17 m) to the east. All four sloping north and east. Possibly these four levels are two levels at different locations, incised by the creek flowing through the low lying stretch of land between A Cunchada and As Medas. On the other side of the low stretch also few low levels can be found. A T4a at As Medas, and a T3a (20-22 m) and a T4a (30-33 m) just south of O Rosal continuing towards the Tamuxe terraces. Further north T5a levels can be found at 39-40 meter at As Medas, O Rosal and the hill dividing the Tamuxe river from the lower lying flat to the west. At As Medas and O Rosal these T5a levels are backed by a T6a level at 48-50 meter. Moving from the Miño river up to A Guarda and around the Sta Tegra also other levels can be found. For example T2a (10-13 m); T3a (20-22 m); T4a (30-33 m); T4b (35-36 m), T5a (39-43 m); T5b (45-48 m); T6b at 55 meter; and the highest level in the O Rosal valley in the middle of the isthmus at La Guarda a T7 at 59-62 meter. More to the west a higher level is found at 62-65 meter, which lies like an island in the landscape. This level is shown in figure 3.

South of A Guarda terrace sequences are present along the Sta. Tegra. In this area the altitudes differ slightly from the other found terraces. T2a (10-13 m), T3a (20-22 m), T4a (30-33 m), T5a (39-43 m) levels are found. Apart from T2a and T5a, these levels do not make another appearance facing the Miño directly, apart from a T2a terrace, which is found west of the Tamuxe river.

These levels are debatable due to very neat and equal terrace edges which suggest the terraces are man made. In A Guarda construction and centuries of habitation have possibly altered the soil to such an extent that hardly any reliable gravel has been found. East of the Sta. Tegra occurrence of gravel proofs that there have been fluvial influences, however it is unclear if the gravel is still in its original place. The highest levels (T5a at 42 m, and T5b at 48 m) are probably natural, further downslope the levels are less convincing and at least some levels are clearly terraced. The whole mountain is covered in eucalyptus trees, a measure often taken to prevent erosion and landslides. The lower levels east of the Sta Tegra (Nr. 59 and 60) can therefore best be taken as a T1b because it has probably been covered by colluvium. South of the Sta Tegra, the found terraces do not show any gravel, only dark soils have been found with sometimes angular quartz or granite.
T6b (55 m) has only one occurrence in the O Rosal valley, directly east of the highest level in A Guarda. Also this level is possibly terraced

In the part along the lower Tamuxe river (part III) a T1a, T1b and a T2a can be found on the western side of the river. A T2b exists as a small island in the landscape northern part of the lower Tamuxe river. On the eastern side only a thin T1 is preserved.
In the upper part of the Tamuxe river (Part IV) small terraces are recognised in the gorge, T1a, T1b, T2a and a T2b. Higher up the slope a T3a at 30 meter is found. A bit further upstream five different levels have been found. A T1a, T1b, T2b, T3b and a T4b. However, the levels are terraced, so it is hard to find true terrace boundaries

In table 5 the terrace levels which are almost certainly formed by the Miño are compared in their altitude. Looking at the occurrence of the terraces, T1a (4-7 m), T1b (8-10 m), T2b (15-17 m), T3b (25-27m), T4b (35-36m), T5a (39-43 m), T5b (45-48 m), T6a (49-51 m) and T7 (59-62 m) are most prominent.

Table 5: The most reliable Miño terraces in the O Rosal valley

O ROSAL-MIÑO NR	ALTITUDE (m.a.s.l.)	TERRACE LEVEL	SUMMARY	
62	4-5	T1a	Range : 4-7	
63	4-5	T1a		
50	5	T1a	AREA (m^2):	
97	7	T1a		**1.009.162**
61	7-8	T1b	Range: 8-10	
52	8-9	T1b		
214	8-9	T1b		
226	8-9	T1b		
123	9-10	T1b	AREA (m^2)::	
67	10	T1b		**488.122**
59	10-11	T2a	Range: 10-13	
227	11-12	T2a		
287	11-12	T2a		
319	11-12	T2a	AREA (m^2)::	
60	12-13	T2a		**183.874**
127	15	T2b	Range: 15-17	
53	15-16	T2b		
68	15-16	T2b	AREA (m^2)::	
230	15-17	T2b		**927.687**
58	20-21	T3a	Range: 20-22	
283	20-21	T3a	AREA (m^2)::	
96	22	T3a		**87.922**
51	25-27	T3b	Range: 25-27	
69	25-27	T3b		
124	26	T3b		
94	26	T3b	AREA (m^2)::	
57	27,5	T3b		**785.846**
9	30	T4a	Range: 30-33	
119	31-32	T4a	AREA (m^2)::	
286	32-34	T4a		**44.335**
95	35	T4b	Range: 35-36	
56	35-36	T4b		
71	35-36	T4b	AREA (m^2)::	
23	38-39	T4b		**788.765**
35	39	T5a	Range: 39-43	
5	39-40	T5a		
116	39-40	T5a		
326	40	T5a		
292	40-42	T5a		
3	41-42	T5a		
303	41-42	T5a		
117	42-43	T5a		
334	40	T5a	AREA (m^2)::	
335	40	T5a		**632.698**
251	44-45	T5b	Range: 45-49	
66	45-46	T5b		
291	45-46	T5b		
46	46-49	T5b		
74	47	T5b		
75	48	T5b	AREA (m^2)::	
118	48	T5b		**689.178**
235	48-52	T6a	Range: 48-51	
4	49-50	T6a		
305	49-51	T6a		
1	50	T6a	AREA (m^2)::	
308	51	T6a		**284.409**
24	53	T6b	Range: 53-55	
33	53	T6b		
240	53	T6b	AREA (m^2)::	
76	55	T6b		**295.159**
65	59-62	T7	Range: 59-62	
			AREA (m^2)::	
				51.718

5.3.2 Sediments in the Rosal valley

In the O Rosal valley many different kind of sediments have been found. There are large exposures consisting of quartzite and quartz gravels, and on the fields quartzite, granite, quartz and gneiss are found.

From north to south exposures of gravel deposits are visible at As Medas, O Rosal, A Cunchada, A Cumeira de Abaixo, at the construction of the new highway, and at the LIDL along the provincial road. A map is made of the area where gravels are found. This map is shown in figure 10. The location of the most important gravel exposures is visualised with a label. The two red dots along the Tamuxe River and the one red dot at As Medas are locations where a sample is taken of the gravels in the present river bed.
First the results from the gravel found on the river terraces is summarized, and then the gravel found in the small creeks. The different exposures are discussed in section 5.6 in more detail.

5.3.2.1 Sediments on the river terraces

As can be seen, in the largest part of PART I of figure 10, quartzite and quartz are found, though not on the highest levels in the west. On these western parts gravel is not found anymore, here only angular quartz and angular pieces of granite in a dark brown silty soil are found on top of granite sapprolite. A boundary is found west of A Cunchada and west of As Medas, where the gravel abruptly disappears, and only sapprolite and granite is found. On the lower levels of PART I (up to T2a) occasional also some granite gravels are found in between the quartz and quartzite gravels.

In PART II Quartz and quartzite are also found at the hills of As Medas and O Rosal, and the area directly below these hills. On the lower flat area between A Cunchada and As Medas, similar quartzite and quartz are found as on the hills, but also granite and gneiss gravels are found. However on the T5a terrace east of O Rosal, gravel has not been found. In the lower Tamuxe valley gneiss, granite, schist gravels are found. On the western Tamuxe terraces these are often mixed with quartz or quartzite gravels. However, on the eastern Tamuxe terraces quartzite gravels have not been found. Higher up the Tamuxe river, at Loureza just of the map, only schist gravels are found.

In Part V only on the terraces east of the Sta. Tegra reliable gravels are found. Moving from the Miño up to A Guarda, the reliable gravels soon cease to be present. Large parts are built up, but occasionally the soil in the gardens can be investigated. Most of the time the soil consists of angular quartz, some angular granite scrapes, bricks and roofing tiles in a dark brown sandy silty soil. At a few places however, also some gravels are lying between the trash. For example, gravels have been found at the 28 m terrace (T3b), 48 m terrace (T5b) and even at the next to highest 60 m terrace (T7). However due to the amount of construction waste lying around it is impossible to conclude whether these gravels are deposited in a natural way.

Gravel in O Rosal

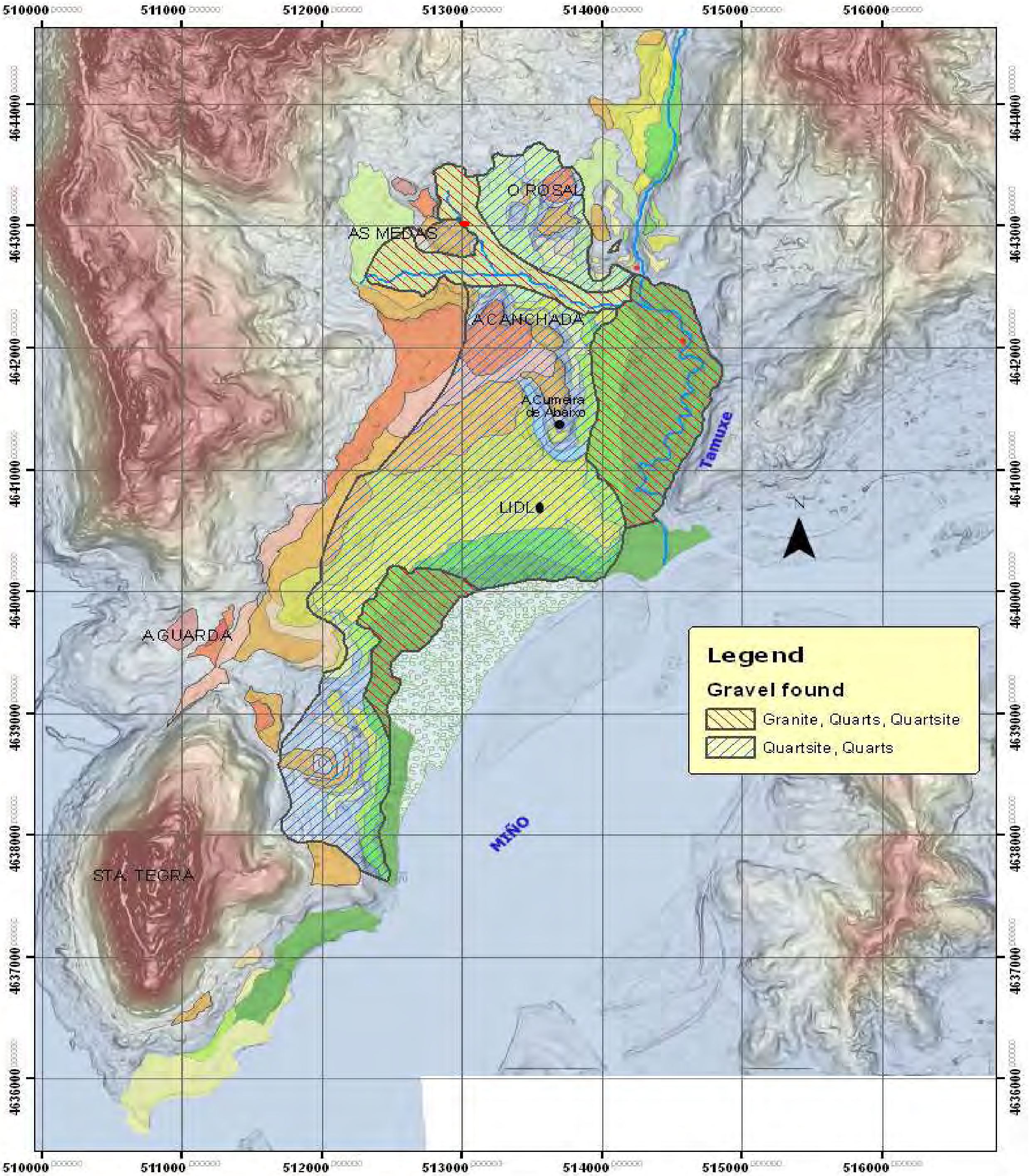

Figure 12 : Gravel found in the O Rosal valley, area without overlay no convincing gravels have been found.

5.3.2.2 Sediments in the Miño and small creeks

At two places the sediment of the current Miño has been analysed: at the O Rosal valley and at As Neves, ± 50 km upstream. Close to the streambed in As Neves gravels were found up to 20 cm in size consisting of quartzite, quartz, granite, gneiss and other rock types. At the O Rosal only fine sediments were found, mostly sand and silt.

At three locations along the small creeks in the area the gravels which are currently transported have been sampled and analysed. This is done below the terrace at As Medas in the tributary of the Tamuxe; and at two places in the Tamuxe river. At the end of the small gorge in the Tamuxe, and downstream of the small creek which enters the Tamuxe. These locations are visualised by red dots on figure 12. The gravels found in the river bed range from 1 cm to 30 cm at As Medas, or over a meter at the other sample points, the gravels are not rounded but rather sub-angular, and are easy to break. But most interesting is the composition of the different samples. The results of this analysis are summarized in table 6.

Table 6: Gravel found in the riverbed of small creeks in the Rosal valley

Location	Sample size	Granite(%)	Quartz(%)	Quartzite(%)	Schist (%)	Gneiss(%)	Other(%)
Small creek below As Medas	40	60	10	20	0	10	0
Gorge Tamuxe	35	60	30	0	0	10	0
Lower Tamuxe	100	36	38	3	9	3	11

Discussion

Fifty kilometres upstream of the O Rosal valley gravel is still transported by the Miño, at the height of the Rosal valley however only fine sediments are present in the current river bed. Since the discharge of the river does not decrease during these 50 km, the flow velocity probably decreases due to a decrease in gradient.

It is noticed that below the T5a terrace at As Medas, large quantities of quartzite are present in the riverbed of the small tributary of the Tamuxe, while the sample at the Tamuxe gorge does not contain any quartzite, and the sample at the lower Tamuxe only 3%. Since the sample at the lower Tamuxe is taken below the point the small tributary and the Tamuxe meet, it is believed these quartzite come from the small creek flowing west-east. It is logical that the small creeks in the north west of the Rosal valley carry quartzite as they are flowing in between the large gravel deposits consisting solely of quartzite and quartz. So probably the Tamuxe river does not carry any quartzite. Since the Miño river is the only source which carries quartzite, it seems obvious that the deposits have been formed by the Miño.

Another possibility would be that the deposits have been laid down by the Tamuxe, but since the deposition another river captured a part of the Tamuxe catchment, capturing the part of the river which cuts into quartzite rock. However, the upper river valley of the Tamuxe does not seem too big for the current discharge, hence the Tamuxe is not a misfit stream, which makes the idea of river capture unlikely (Summerfield, 1991). Also the DEM does not show signs of river capture by other creeks close by and none of the geological maps of the Tamuxe river, and its surrounding creeks up to Baiona and the valley east of the O Rosal valley mention any occurrence of quartzite in their catchments (Pliego Dones and Corretge (1978), Abril Hurtado and Corretge (1978), so the only source seems to be the Miño river.

At the moment the Miño does not have the power to carry gravels to the O Rosal valley, which means the deposits have been formed in a more energetic environment than the present, with either a higher discharge or a steeper gradient (Bagnold, 1973 in Stemerink et al. 2010).

It is remarkable that the present Miño carries granite and gneiss gravels, as these have only been found on a small part of the T1a/T1b terrace, but not on higher altitudes. Possibly the granite and gneiss gravels on the older terraces disappeared due to weathering, leaving only the more resistant quartz and quartzite gravels behind (Repka et al., 1997; Howard et al., 1995).

Conclusion
So it can be concluded that the large gravel deposits, and the terraces in PART I have not been formed by the Tamuxe, but rather by the Miño. These deposits have been formed in a more energetic environment. Possibly quite some time ago, as only the most resistant gravels (quartz and quartzite) are found back on the terraces and in the deposits.

5.3.2.3 Comparison of fluvial terrace levels Rosal with literature

In this chapter all the terrace levels found in literature in the study area are shortly mentioned and compared to my own findings. First the results from the research of Nonn (1967) are discussed, afterwards the findings from Butzer (1967) and ultimately the findings of Cano Pan et al. (1997). Table 7 shortly summarizes what other authors have found in the study area, and compares my findings with the older researches.

Table 7: Comparison of the found terraces and altitudes by other authors with my own findings in the O Rosal valley.

ROSAL		
Nonn	**Altitude**	**Own findings**
Church Salcidos	12-18mts	Yes, at T2b, 12-17 meters
Cemetary Rosal	56mts	Yes, at T6a, 50 mts.
A Cunchada	40-45mts	Yes, at T6a, 48-49mts
Cathedral Rosal	40-45mts	Yes, at T5a, 40mts.
Isthmus A Guarda	56mts	Unsure location. Levels found at 57mts closeby.
Butzer(1967)		
Low terrace	18mts	No. T3a could at places begin at 18meters, though not convincing
Middle terrace	44mts	No. Levels in the Rosal valley are either at 39-40mts. (T5a) or at 48-50 mts (T6a)
Cano pan et al. (1997)		
A T1, T3 and T5 following each other moving North up into the Rosal valley	2-9mts & 19-28mts & 42-55mts	Yes, however subdivided in seven steps, moving up to 49mts. T6a.
A thin T1 stretch moving N up into the Rosal valley, almost up to A Canchada.	2-9mts	No, this is weird, because there is not even a lower part there.
A T2 stretching longtidunal N-S parallel to the Tamuxe river (A Canchada to river mouth of Tamuxe).	10-19mts	Yes, it has been found ranging from 9-20mts.
A T3 As Medas & Rosal	19-28mts	Yes, but a T5a at 40mts.
A T2 North-east of Canchada a small terrace	10-19mts	Yes, found at 14-20mts. Subdivided in three steps, from 8mts up.
A T2 south of O Rosal	10-19mts	Yes, a T3a at 20-21mts and a T4a at 32-34mts.
A T7 at the ancient Miño channel	65-72mts	Yes, found between 59-62mts
A T5 and T4 level east and west of the isthmus	42-55mts & 32-42mts	Yes, a T6a around 48-50mts. A convincing level incised by a small creek. The lower levels are however no real terrace levels, but are flattened by erosion.
A T3 at Camposancos	19-28mts	Yes, it is a T4b at 35mts instead of a T3.
A T1 and T2 run up to the point of the Sta Tecla (2-9mts) & (10-19mts)	2-9mts & 10-19mts	A continuous T1a at 4-7mts; a T2a at 11-13mts; a small T3a at 20mts and a T4a at 38mts are found, however nothing continuous nor very convincing.
A T7 and T4 north of O Rosal	65-71mts & 32-34mts	No. There are flats north of O Rosal. However, these are all higher than 40 mts. These are not terraces as they do not have clear terrace incision edges.

In general my results correspond with the results of other authors, especially with Nonn's work (1967). Though he only mentions a few obvious places. In quite some instances I do not agree with Butzer (1968) or Cano Pan et al. (1997). I find more or less the same trend as Cano Pan et al. (1997), only I make a more detailed subdivision as they have done. However, in a few places I strongly disagree with them. At quite some locations they mention terraces and I am positive there are none.

As noticed earlier, while discussing the marine terraces on the Spanish and Portuguese coast, the terrace heights do not always match, even though the location of the terrace is exactly the same. The difference in altitude are probably not caused by a mistake by me, nor of the other authors. But rather caused by the available source used for altitude. In table 8, the altitude, as found on different maps of several important terraces in the O Rosal valley is compared. This table shows that there is quite some divergence, ranging from 10 to 28 meter. The vertical accuracy of the different maps also differs (resp. 5 m for the maps of the Xunta, 10 m for the geological maps and 10 cm for the DEM).

Table 8: Differences in altitude of some important terraces in the Rosal valley
(All values in m.a.s.l.)

Location/ Maps	Xunta 1:5.000	Geological map (1:50.000)	DEM (5m grid)	Range
Top Cem. Rosal	56	35-45	51,8	35-56
As Medas (m)	44,9	35-45	39,9	35-44,9
A Cunchada	50,4	45-55	49,6	45-55
Lidl exposure	20-23.9	35-45	17-20	17-45

This makes analysis and comparison of the terraces heights difficult, especially since I was not able to use the same source for all the terraces. However, some terrace altitudes do occur more often than others.

5.3.3 Conclusion

For the O Rosal valley the most prominent terrace levels were, T1a (4-7 m), T1b (8-10 m), T2b (15-17 m), T3b (25-27 m), T4b (35-36 m), T5a (39-43 m), T5b (45-48 m), T6a (49-51 m) and T7 (59-62 m). Other parts are probably man-made terraces or have been formed by other creeks.

5.4 Comparison of all the terrace levels

In this chapter I shortly compare the altitudes and sediments of the three parts of the study area.

5.4.1 Terrace levels

Several terrace levels have been found along the Spanish coast, the Portuguese coast and in the O Rosal valley. In this chapter these levels are compared. The most prominent and reliable terrace levels have already been mentioned in the last chapter. These are visualised in table 9.

Table 9: Comparison of the most reliable terrace levels along the Spanish coast, Portuguese coast and in the O Rosal valley

Spanish coast	Portugese coast	O Rosal	General terrace height range	Average height
T1(5-10mts)	T1(5-10mts)	T1a(4-7mts) T1b(8-10mts)	T1(5-10mts)	7
T2a(11-15mts)				
	T2b(14-17mts)	T2b(15-17mts)	T2(14-17mts)	15
T3a(18-22mts)	T3a(20-25mts)		T3(18-25)	20
	T3b(25-28mts)	T3b(25-27mts)	T3(25-28mts)	26
T4a(28-33)	T4a(28-33mts)		T4(28-33mts)	29,5
T4b(33-38mts)		T4b(35-36mts)	T4b(33-38mts)	35
T5(39-43)	T5a (38-41mts)	T5a(39-43mts) T5b(45-48mts)	T5(38-41mts)	40
T6(47-50mts)	T6a(48-52mts)	T6a(49-51mts)	T6(47-52mts)	50
T7(57-62mts)	*T7a(58-62)*	T7(59-62mts)	T7(59-62mts)	60
T8(62-67mts)				

As can be seen most levels correspond well. Only for the T2a level along the Spanish coast, and the T5b level in O Rosal-valley, reliable corresponding terraces are not found in the other parts of the study area. The T1 level has been subdivided in the Rosal valley, which has not been done on the coast. Along the Portuguese coast the T7a level is taken into account after all. Even though it was thought to possibly be coincidentally flat, reliable terraces are found in both other parts of the study area at the same altitude.

The heights of the terrace levels correspond almost perfectly between the Spanish coast, Portuguese coast and the O Rosal valley. From this it can be concluded that since the formation of the highest terrace at 60 meter, the different parts of the study area have probably not moved relative to each other. In other words differential uplifting did not take place in the study area since the formation of the terraces. This is interesting because the Miño is believed to run through a thrust fault along which the Portuguese part is pushed under the Spanish part (Vegas, 2009). This implies this fault has not been very active since the formation of the 60 m terrace. It is interesting to know when these terraces were formed. However in the area few possibilities exist for dating (Cano Pan et al., 1997; (Alonso and Páges, 2007), and none of the authors give a conclusive age of the described features. Consequently, an uplift rate for the area is not known.

It is believed that sea level is of large influence on the formation of the terraces in the study area. Sea level is the base-level of the fluvial terraces, and therefore more or less the top of the terraces in the O Rosal valley. Sea level is also the altitude at which marine benches are cut and marine terraces are formed. Therefore the marine and fluvial terraces T1, T2, T3a, T3b, T4, T5, T6 and T7 as found in table 9 are most probably formed at the same time. Probably during inter-glacial sea level high-stands, because terraces formed during high-stands the sea level is stable for a long period of time. Because the sea level is high during inter-glacial periods, the terraces formed are most probable to still be visible in the landscape. Possible terraces, formed during glacial periods or temporary stalling transgression or regression, are probably submerged right now.
In section 5.5 the most important high-stands are shown in the Quaternary.

5.4.2 Comparison of the gravel on the terraces

In all three parts of the study area gravels are present up to 50 m. Granite, schist and gneiss gravels occur along the Tamuxe and its side creek. up to the T1b terrace along the Miño granite, quartzite, quartz and gneiss gravels are found. Along the coast up to 20 m quartzite, granite and gneiss gravels can be found. On the higher marine terraces only quartzite remains, and in the O Rosal valley, only quartzite and quartz are present on the higher levels. On the marine terraces the gravels are all very fresh, though they are very weathered in the O Rosal valley.
Because the Miño river is believed to be the only source of quartzite in the area, the gravel along the coast and in the O Rosal valley has probably been carried to the study area by the Miño (Pliego Dones and Corretge (1978), Abril Hurtado and Corretge (1978), Carta Geologica de Portugal).

A few possibilities for the difference in weathering are discussed here.
The gravel deposits along the Miño river could be much older than the terrace formation, and subsequently underwent more chemical weathering.
Another possibility is the gravel in the O Rosal valley is weathered more rapidly than the gravels along the coast. Wet and warm circumstances favour chemical weathering of rocks (Tebbens and Veldkamp, 2001). Gravel deposits consist of gravels, sand and clay which retain water (Bachman and van der Ploeg, 2002; van Genuchten, 1980). The capacity to maintain a temperature, or thermal inertia, is a function of thermal conductivity, heat capacity and bulk density (Hejmanowska and Stanislaw, 1996). The Thermal inertia is higher inside the deposit than outside the deposit ("Specific Heat Capacity Table"; " Thermal Conductivity of Some Common Materials").
So within a gravel deposit the temperature is more stable, and water is better retained. This makes it possible that the chemical weathering of the gravels is faster within the gravel deposits than outside the gravel deposits.

The gravels which end up along the coast on the other hand have been reworked on the beach for a long time (Johnson and Libbey, 1997), during which the weaker clasts already broke and disappeared, consequently only quartzite remains. As there has not been found a convincing buried marine deposit, the marine gravels which were found are more exposed. Chemical weathering is possibly slower, and weaker gravels have already been destroyed by physical weathering.
Looking at the granite in the area, we see the same trend. The hardrock which is buried under a gravel deposit or forest soil is always very weathered, while granite which is exposed at the surface, seems quite hard. Possibly the weaker bits are eroded faster when the hardrock is not buried.

5.5 Sea level analysis

In this chapter a possible relation between sea level and terrace formation is investigated. Because marine terraces are believed to be formed during sea level high-stands (James et al, 1971; Hearty et al., 2007; Summerfield, 1991; Burbank and Anderson, 2001) the sea level high-stands are investigated in this section. In theory every time the sea level is stable a marine terrace is formed, in shorter periods of stable sea level small terraces or notches are formed, while larger periods; or repeated periods of constant sea level at relatively the same altitude lead to larger marine levels (Hearty et al., 2007; Burbank and Anderson, 2001; Alvarez Marrón et al., 2008). However, the length of the sea level high-stands in correlation with the terrace size has not been taken into account in this analysis. The size of the terrace levels is thought to be strongly influenced by erosion, as the older levels cover less area than the younger terrace levels, though it must be mentioned that the 30 m and 40 m terrace are relatively large in size. Also the possibility of terrace formation during temporarily stalling sea level in trans- and regressions has been ignored in this analysis. As very few notches in the sea level curve can be recognised, and in order to match a terrace level with these notches, a strongly fluctuating uplift rate is needed, for which there have not been found any indications.

5.5.1 Former sea level

Sea level is thought to have fluctuated in the past, forced by processes. These processes are believed to be cyclic (Miall, 1997). In this paragraph these cycles are shortly discussed.

5.5.1.1 Geological cycles

There are four large stratigraphic cycles which are recognised in the history of the planet, influencing geological events, amongst others sea level fluctuation and deposition of sediments. The first order has a duration of 200-500 My and is related to formation and breaking up of the mega-continents. The second order fluctuations have a returning period of 10-100 My and are related to sea floor spreading and basement movement. The third order cycles occur every 0,1-100 My and are caused by local tectonics, and changes in intra-plate stress regimes. At last there are the fourth order cycles which have a reoccurrence time of 100-2000 ky, which are caused by orbital forcing and influence sea level and productivity cycles (Miall, 1997).

Differences in orbital forcing cause the climate to change, and cause the formation and the melt of ice packs. The amount of water packed in ice in turn influences the global sea level, this orbital forcing are called the Milankovitch cycles (Miall, 1997).

it is believed that for the formation of the marine terrace levels in the study area the fourth order cycles, and especially the Milankovitch cycles are the dominant cycles behind the sea level fluctuation. Although the longer cycles also strongly influenced the sea level in the past (Miall, 1997; Miller et al., 2005). These cycles are believed to take too long. Several terrace levels have been found along the coast, if the terraces would be formed by a sea level high-stand which re-occurred every few million years, not many levels would be visible in the present topography because they would have been eroded away.
Next paragraph shortly gives some more information on the Milankovitch cycles.

5.5.1.2 Milankovitch cycles

As mentioned in the last paragraph the Milankovitch cycles are cycles of orbital forcing, or solar influx on the earth. The amount of solar influx depends on the distance of the earth to the sun. Three different cycles have been identified which influence the sun shine received by the earth: The axial precession, or the wobble around the earth's axis (cycle of 23 ky); the tilt of the earth's axis towards the sun (cycle of 41 ky); and the eccentricity of the path the earth makes, turning around the sun (cycle of 100 ky) (Beedle, 1999). The solar influx influences the temperature on earth and in that way influences the amount of water which precipitates as snow and is captured on land.

The amount of water captured in snow and ice, in turn influences the global sea level (Miall, 1997). From oxygen isotope ($\delta^{18}O$) analyses is concluded, that the last 800 ky the 100 ky-cycle is the most important, and before 800 ka the 41 ky-cycle was most important. This means that more or less similar circumstances return every 100 ky (Miller et al., 2005). Because it takes a while to capture precipitation in snow and ice, it is believed that during periods in which the 41 ky-cycle is dominant, less fluctuation of sea level can be expected than during periods in which the 100 ky-cycle is dominant.

Consequently during inter-glacial periods in which little water is captured in ice, sea level is relatively high, while during glacial periods the , while during glacial periods the sea level is low because a lot of water is trapped in continental ice sheets. The sea level fluctuated between – 125m to + 100 ±50m over the last ~80 million years (Miller et al., 2005). And fluctuate between - 125 m and + 20 m in the Quaternary (Berger, 2008; Bintanja and van de Wal, 2008 in de Boer et al., 2010; Bintanja et al., 2005; Broeker et al. et al., 1968; Chapell and Shakelton, 1986; Dorale et al., 2010; Dutton, et al. 2009), as will be discussed in the next paragraph. The last 800 ka 8 inter-glacial periods are recognised, which mostly show one large peak in sea level, surrounded by one or two lower peaks (Bintanja et al., 2005).

5.5.1.3 Sea level fluctuation

The sea level has a large influence on the formation of marine and fluvial terraces. The former sea level is the level at which the marine benches are cut and is the top of fluvial terraces near their estuary. Below a figure of the sea level fluctuations over the last 800.000 years is shown, and the most important sea level high-stands are shortly mentioned in table 5.11.

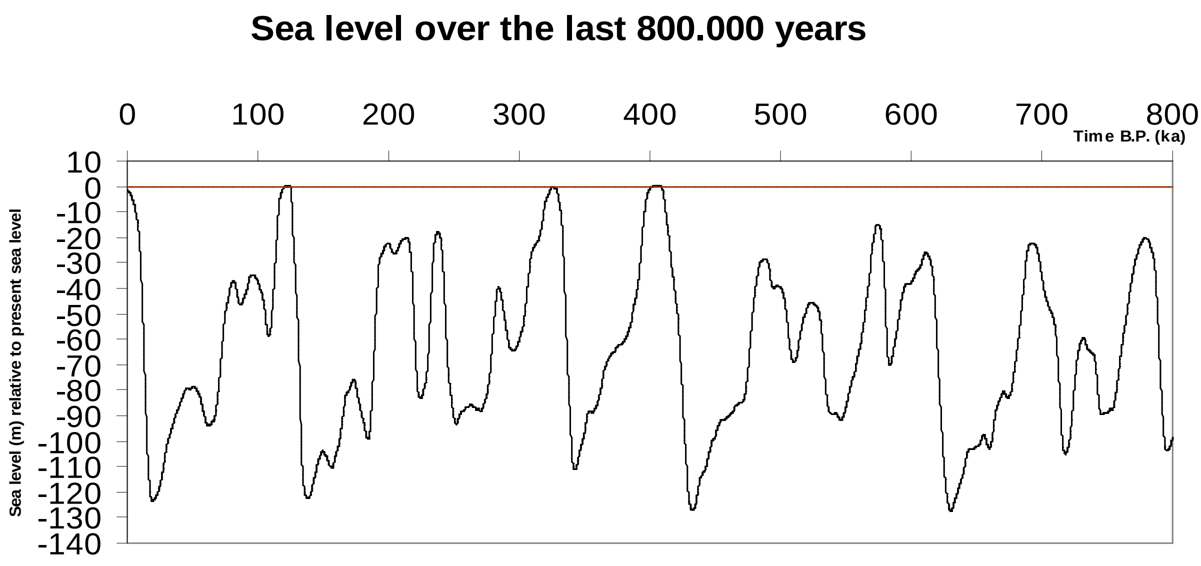

Figure 13: Sea level over the last 800 ka (source Bintanja et al., 2005)

As can be seen from figure 13 there have been three other periods in which the sea level has been more or less the same as the present sea level. These levels took place about 120 ka, 340 ka and around 400 ka. In general authors agree on the age of the sea level maximums (Berger, 2008; Bintanja and van de Wal, 2008 in de Boer et al., 2010; Bintanja et al., 2005; Broeker et al., 1968; Chapell and Shakelton, 1986; Dorale et al., 2010; Dutton, et al. 2009) though there are slight differences of a few ky. However, the exact height of the different events differs, as can be seen in table 10.

Apart from the levels already mentioned in table 10, Bintanja et al. (2005) also find maximums at 776 ka (-21m); 730 ka (-60m); 610 ka (-27m); 572 (-16m); 520 ka (-47m); 484 (-29m); 322 ka (0m); 283 ka (-41m); 93 ka (-36m). Like already mentioned the differences in estimated sea level are quite large. At MIS 3 estimated sea level ranges from 40 to 78,5 meter below present sea level, and even the estimates for the well investigated MIS 5e range from 0 to 6 meter above present sea level (See table 11).

During the whole Quaternary not a single sea level is mentioned above 21 m (Berger, 2008; Bintanja and van de Wal, 2008 in de Boer et al., 2010; Bintanja et al., 2005; Broeker et al., 1968; Chapell and Shakelton, 1986; Dorale et al., 2010; Dutton, et al. 2009). The highest sea level mentioned (400 ka) lies at + 20-21 meter (Hearty et al., 1999; Olson and Hearty, 2009), although convincing terrace levels have been found up to 62 meter. So it is clear that if the terrace levels have been formed in the late Quaternary, uplift must have taken place. Although only for the past 6000 years, and some 80 km south of the study area, Granja (1999) indeed finds an uplift rate of max. 1,4 mm/y on the Portuguese coast.

Table 10: Sea level high-stands by different authors

MIS	Years	Height	Source	Height (Bintanja et al. 2005)
MIS 1	5 ka	0	Broeker et al., 1968; Chappell and Shackleton, 1986	-6,6 (No maximum)
MIS 2	18 ka	-150	Broeker et al., 1968; Chappell and Shackleton, 1986	-123,4 (Minimum at 19,6 ka)
MIS 3	40 ka	-40	Broeker et al., 1968; Chappell and Shackleton, 1986	-78,9 (Maximum at 46,2ka)
MIS 4	62 ka	-28	Broeker et al., 1968; Chappell and Shackleton, 1986	-93,9 (Minimum at 93,6 ka)
MIS 5a	80 ka	-19	Broeker et al., 1968; Chappell and Shackleton, 1986; Dorale et al., 2010	-36,9 (Maximum at 81,2 ka)
	85 ka	1	Dorale et al. 2010	-45
MIS 5c	100ka	-38	Broeker et al., 1968; Chappell and Shackleton, 1986	-34,7 (Maximum at 96 ka)
MIS 5e	120ka	0	Broeker et al., 1968; Chappell and Shackleton, 1986	0,4
	125 ka	3	Blanco Chao et al. 2002	(Maximum at 124,3 ka)
		6	Bloom & Yonekura, 1990	
		0,857142857	Mylroie, 2009	
MIS 6.5	167± 1 - 176± 3ka	-48	Scholz, Mangini and Meishner, 2007	-75,6 (Maximum at 173,1 ka)
MIS 7.1	± 195	-21	Dutton, Antonioli and Bard, 2009	-22,3 (Maximum at 199,7ka)
MIS 7.3	± 210	-18.5	Dutton, Antonioli and Bard, 2009	-20 (Maximum at 215-210 ka)
MIS 7.5	± 240	-48	Dutton, Antonioli and Bard, 2009	-17,8 (Maximum at 237,6 ka)
MIS 11	420 – 360 ka	+20 – 21	Hearty et al., 1999; Olson& Hearty, 2009	0,3 (Maximum at 403,3 ka)
	± 400 ka	± +10	Berger, 2008	
MIS 15	± 620 ka	± -12	Berger, 2008	-26 (Maximum at 611,2 ka)
MIS 25	± 950 ka	± 0	Berger, 2008	
		-4	Bintanja and van de Wal , 2008	

Because the sea level high-stands are partly caused by climate change, which is in turn influenced by the Milankovitch cycles, sea level high-stands occur periodically. This means that a sea level high-stand more or less occurs at fixed time intervals. The last 800 ka this cycle was 100 ky, before 800 ka a high-stand occurred every 41 ky (Miller et al., 2005). Burbank and Anderson (2001) mention that fixed time intervals between the occurrence of sea level high-stands, in combination with a steady uplift rate leads to terrace levels at more of less the same height intervals. Although the height intervals are indeed regular between the terrace levels (5/ 10m), as can be seen in table 9, due to the large differences in sea level high-stand, one would assume that actually a fluctuating uplift rate is needed to form terraces at fixed height differences.

5.5.2 Formation of the terrace levels

Even though reliable information on the ages of the terraces is not present and authors seem to disagree on the exact sea level during the last high-stands, in this chapter a possible age and formation of the different terraces is investigated. First the possible age is analysed by varying a constant uplift rate, the second analysis uses variable uplift rates, and is based on dated deposits close to the study area, and the last analysis is done on possible correlations between sea level and the terrace heights, based on the results of the first two analyses.

5.5.2.1 Marine Terraces

Marine platforms are formed at the former sea level at times the sea level is relatively stable. This happens during inter-glacial periods (James et al., 1971). It seems logical that if during regression or transgression the sea stalled a while, also a terrace can form. However, because not every stall in sea level is visible on the graphs made by Bintanja et al., 2005; Bintanja and Van de Wal, 2008 in de Boer et al., 2010; and Lisiekci and Raymo, 2006, this is not taken into account. A possible cause is that $\delta^{18}O$-data on which the graphs are based, do not capture every fluctuation in sea level (Hearty et al., 2007).

5.5.2.2 Fluvial terraces

As mentioned in the last section, most of the terrace levels found in the Miño valley correspond well with the terraces along the coast. This leads to the presumption that the terraces were formed during inter-glacial periods, at the same time the marine terraces were formed, and incised due to base level drop.

However all inter-glacial periods have a more or less similar wet, warm climate as present, with similar vegetation, river discharge and sediment load (Cheddadi et al. 2005; Sanchez-Goñi and Desprat). So we should expect similar sand and silt beneath the terrace levels, just as presently carried by the Miño, but instead of gravels up to 15 cm in size are found. The deposits have been formed in a more energetic environment, when the river was able to carry larger particles. The more energetic environment can be caused by river capture, a higher gradient due to a drop in sea level, by climate change, or a combination of these processes. In a colder climate, less vegetation is present and more runoff is present in the rivers.

Bull (1991, in Tebbens et al., 2000) found that increase in sediment availability due to climate change, can cause a delay in the incision of the river channel, even though base level lowering takes place. A similar phenomena as Schumm and Parker (1973) described. In the analyses of Stemerdink et al. (2010) of the sedimentation and aggradation in the upper Thames river in England, they show that deposition especially took place during change from glacial to inter-glacial and from glacial to inter-glacial. In their model they correct for cold and transition periods as relatively more precipitation enters the river, and for transition periods, as more fluvial activity is thought to take place. Tebbens et al. (2000) use a formula of the average annual runoff, which shows that during inter-glacials more runoff is created, with the top of the peak just before the inter-glacial maximums, this can be seen in figure 14. A changing environment in combination with high flows can carry large sediments, and a rising base level offers opportunities for sedimentation.

When the deposits were formed in the O Rosal valley, the sea level was relatively up to 50 m higher in the study area. This means that the lower Miño formed a bay near the O Rosal valley, however the deposits in the O Rosal valley consist of gravels. In order to deposit gravels, a higher flow velocity is needed, than present in a bay. As the O Rosal valley is sheltered from the sea, the gravels have probably been deposited by the Miño river. However, not during a stable inter-glacial maximum, as during these times the gradient of the lower Miño is very low and a stable climate offers few little possibilities for the river to carry large sediment loads.

Deposition probably took place at the turn from inter-glacial to glacial and at the turn from glacial to inter-glacial. During the turn form inter-glacial to glacial climate deteriorated, vegetation upstream became scarcer, and more water and sediment became available. Possibly the Miño already started to incise increasing the gradient of the river, also leading to more capacity to carry sediment. Because the marine terrace levels and fluvial terrace levels in the area seem to correspond very well, it is believed that deposition took place close to the inter glacial period, when the Miño was still more or less flowing at sea level. During the transition from glacial to inter-glacial the snow and ice in the mountains feeding the Miño started to melt, causing large discharges. In combination with a transgressing sea, this favoured circumstances for deposition in the lower Miño.
Incision probably took place at the turn to the inter-glacial, due to base level drop.

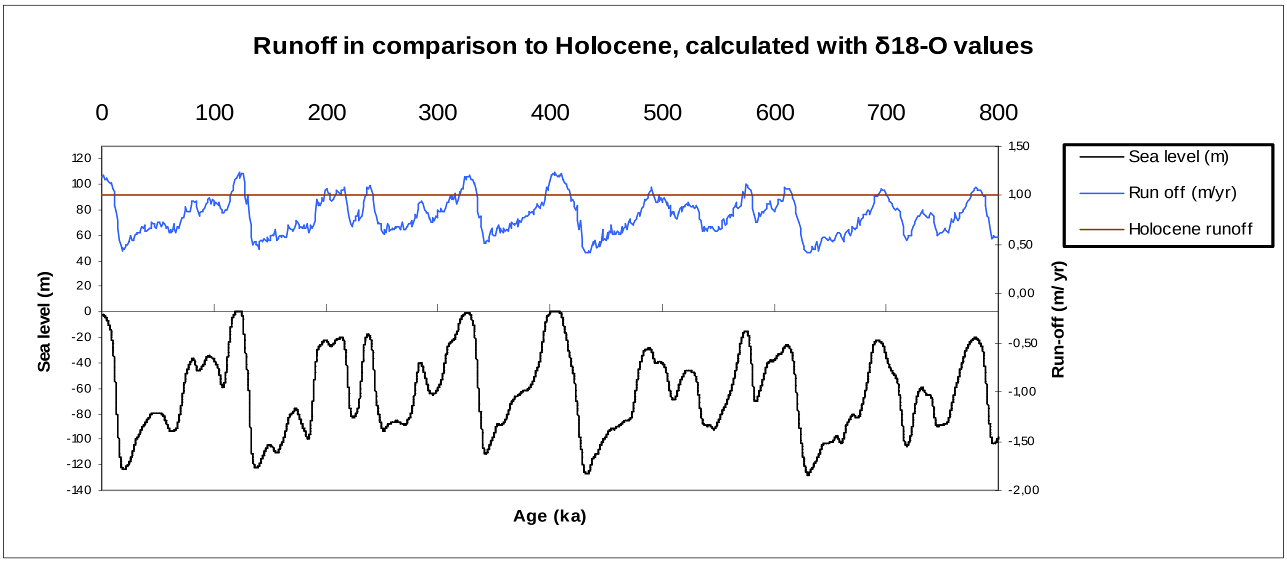

Figure 14: Runoff and sea level relative to present over the last 800 thousand years.
(Sealevel data: (Bintanja et al., 2005) – δ18O data Lisiecki and Raymo, 2005)

$$\text{Run off (m/yr)} = (\text{Present Run off} * \delta^{18}O + 1{,}77) / 2.23$$

Formula 1: Past run off calculated with δ18O data
(Source: Berger and Mugie (1994) in Tebbens et al., 2000)

If we want to find out when which terrace is formed, we can use the same analysis for the marine and fluvial terraces, as they are probably bound by the same tectonic uplift and are formed during more or less the same time. The difference is fluvial terraces form rather at the beginning and end of the inter-glacial, while marine terraces are formed during the whole stable sea level period.

5.5.2.3 Uplift

From the comparison between terraces sequences and sea level height, it seems probable that the study area has been uplifted during the late Quaternary (see section 5.5.1). When an indication of the uplift rate is known for the area, we can analyse possible ages of the different marine and fluvial terraces. However, due to the problems of dating in the area, this is not known. Blanco Chao et al. (2006), Blanco Chao et al. (2002), Texier and Meireles (2000) and Alonso and Pagés (2007) find that the lowest terrace level is formed during the last inter-glacial MIS 5e, around 125 ka ago. This looks defendable as the Eemian was the last long inter-glacial high-stand in the past, and the T1 is found back along almost the whole coast. A problem is that the authors find the lower level between 1,5-3 m (Alonso and Pagés, 2007) and 3-5 m (Texier and Meireles, 2000), where as this research finds the lowest level between 5-10 m. Still, as the locations of my terraces correlate well with the terrace location of Texier and Meireles (2000), it is believed that also my lower terrace can be assigned to the last inter-glacial high-stand.

In this section some analyses are done to find a possible age for every terrace level. In paragraph 5.5.2.4, this is done with a constant uplift rate; in 5.5.2.5 an age control factor is taken into account, using the preliminary results of dated Miño deposits; in paragraph 5.5.2.6 the analysis is done with average varying uplift rates, and uplift rates varying over time. The fourth analyses are explained in 5.5.2.7, and are done with varying uplift rates over time and the dated deposits taken into account. The last analysis in 5.5.2.8 investigates the possibility of terrace levels merged together with both a constant and a varying uplift rate over time.

5.5.2.4 Terrace formation with a constant uplift rate

At a constant uplift rate the lines connecting the terrace levels with the sea level high stands are parallel and straight. This means they are constant over time. This analysis is for instance used by Merrits and Bull (1989), Tellinghuisen, and is explained by Burbank and Anderson (2001).

The lowest terrace level lies at 7 meter altitude, is formed 125.000 years ago at a sea level which ranged between +0 m and +6 m (Broeker et al., 1968; Bloom and Yonekura, 1990; Bintanja et al., 2005). Putting this information in formula 2 the uplift rate varies between: 0,008 mm/y and 0,056 mm/y. If the graph of Bintanja, et al.(2005) is correct, the sea level at MIS 5e was +0,4 m, which leads to an uplift rate is 0,0528 mm/y.

Uplift rate (mm/y)= Terraceheight (m) - Former sea level (m) / Age (ky)

Formula 2: Calculation of uplift rate from the different terrace levels

The results, visualised in figure 15, show that at an uplift rate of 0,0528 mm/y the 7 meter terrace is formed during MIS 5e (125 ka); the 15 meter terrace is formed during MIS 9 (325 ka); and the 20 meter terrace during MIS 11 (400 ka). All higher levels are older than 800 ka of age. The 15 meter and 20 meter terraces are possibly reused. The 15 meter terrace had already been formed during MIS 15 (690 ka) and MIS 13 (570 ka). During MIS 11 this level was submerged, possibly partly destroyed, after which it the current terrace was formed during MIS 9. The 20 meter terrace had been formed during MIS 19 (780 ka), and was reused during MIS 11 to form the final terrace. This process of reusing of marine terraces is described by Burbank and Anderson (2001) and Alvarez- Marrón (2008).

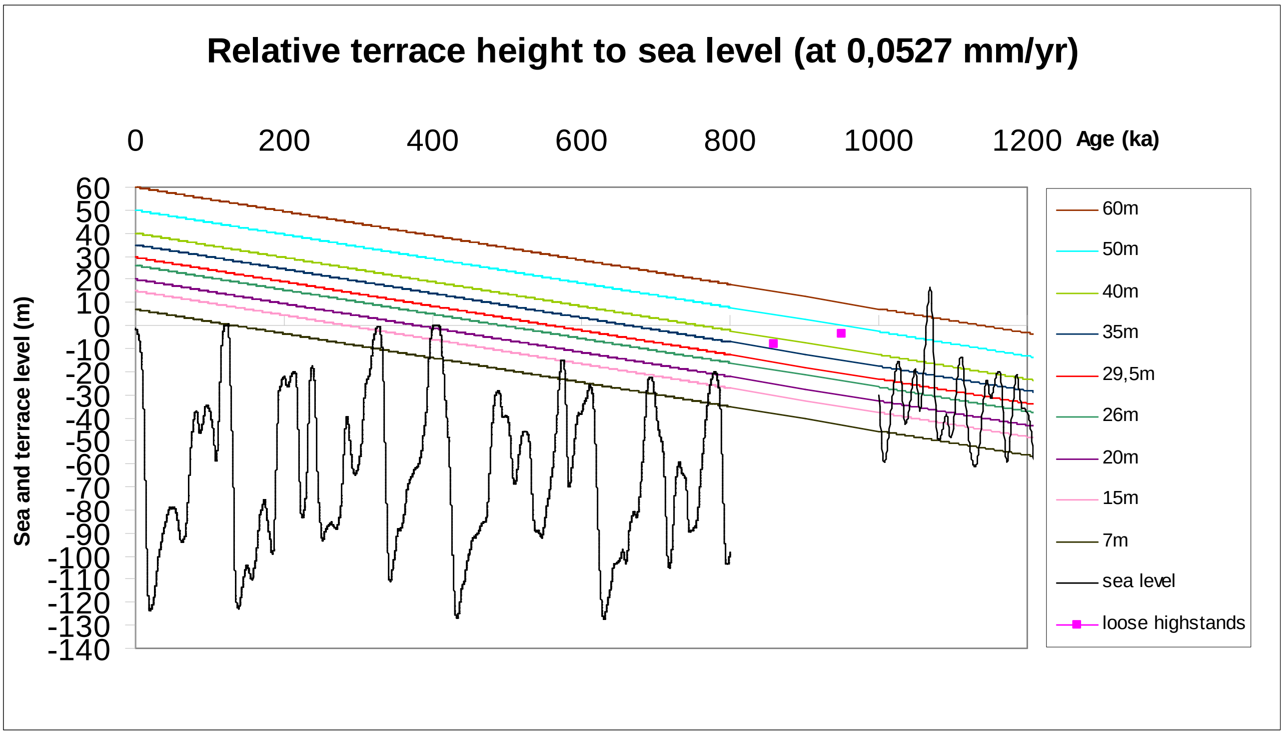

Figure 15: Comparison of terrace levels with past sea level at an uplift rate of 0,0528mm/y
The lines show the correlation between the different terrace levels and sea level high-stands.
(Source sea level data: Bintanja et al., 2005; Bintanja and Van de Wal, 2008; Lisiekci and Raymo, 2006)

Because the uplift rate in this scenario is small, the higher terraces (26 m and higher) would possibly be formed before 800 ka. Therefore other data are used to complete the graph. Two loose high-stands (-8 m at 860 ka, and -4 m at 950 ka) (Bintanja et al., 2005), and a sea level curve of before 1 Ma, of Lisiecki and Raymo (2005).
When we use the sea level data from the last 1200 ka, the results are poor. Possibly MIS 21 and MIS 25 (resp. 860 ka and 950 ka) are responsible form the 40 and 50 meter terraces. This leaves the 26 m, 29,5 m, 35 m and 60 m terrace, which do not match with a sea level high-stand.

It should be noted that in this scenario, the high-stands during MIS 7 (± 200 ka) and MIS 13 (± 500 ka) did not result in terraces, because during those inter-glacials the sea level did not reach the presently current terraces, hence terraces possibly formed during MIS 7 and 13 are submerged right now.

If we repeat the analysis with a higher, stable uplift rate and assume the lowest terrace level was formed during MIS 5a, the problem is that less agreement exists on the sea level. The sea level ranges from 1 to -36,9 m.a.s.l. at around 85 ka. This leads refers to an uplift rate between 0,0706 and 0,517 mm/y. A very large range. As the most complete data set is from Bintanja et al. (2005), their sea level and hence the largest uplift rate is used.

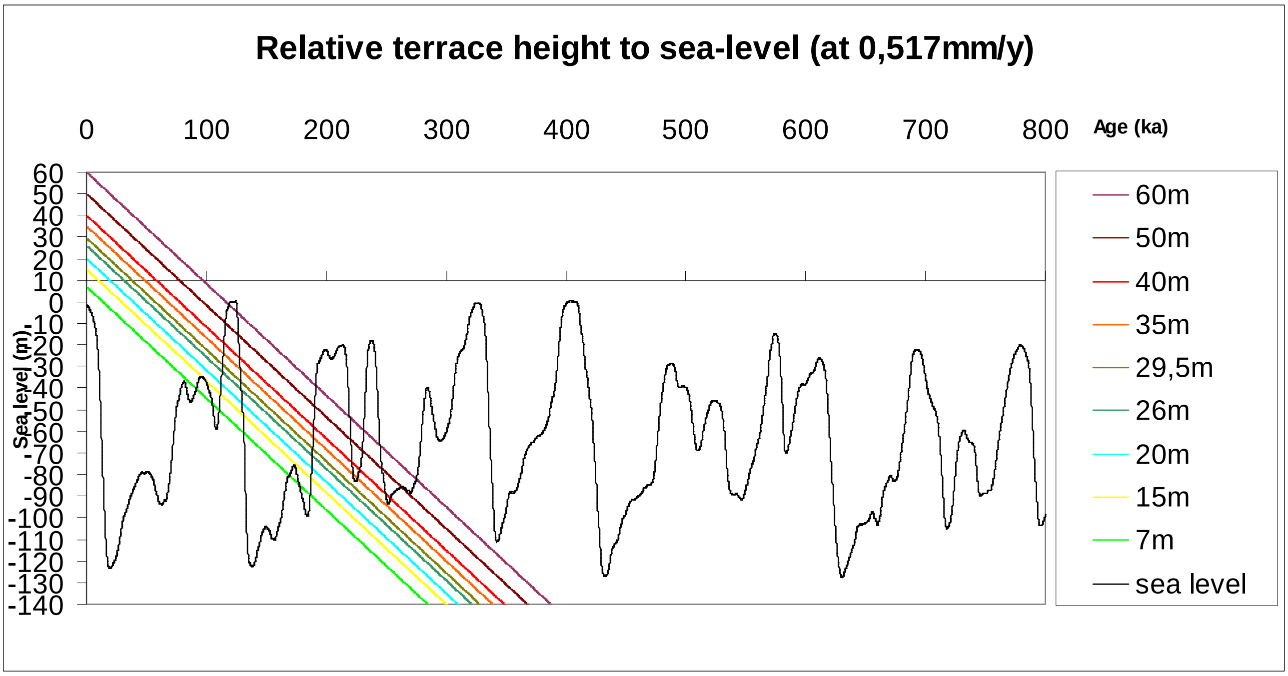

Figure 16: Comparison of terrace level with past sea level at an uplift rate of 0,517 mm/y
The lines show the correlation between the different terrace levels and sea level high-stands.
(Source sea level data: Bintanja et al., 2005)

The results at an uplift rate of 0,517 mm/y are not realistic as can be seen in figure 16.
7 m terrace would be formed during MIS 5a (85 ka), 15m during MIS 5c (100ka) and the 60 m terrace during MIS 5e (125 ka). For the terraces in between a corresponding high-stand found has not been found.

To find out in what range the uplift rate gives the best results, three graphs are shown below. The comparison of the terrace levels with past sea level at an uplift rate of 0,075, 0,110, and 0,250mm/y respectively.

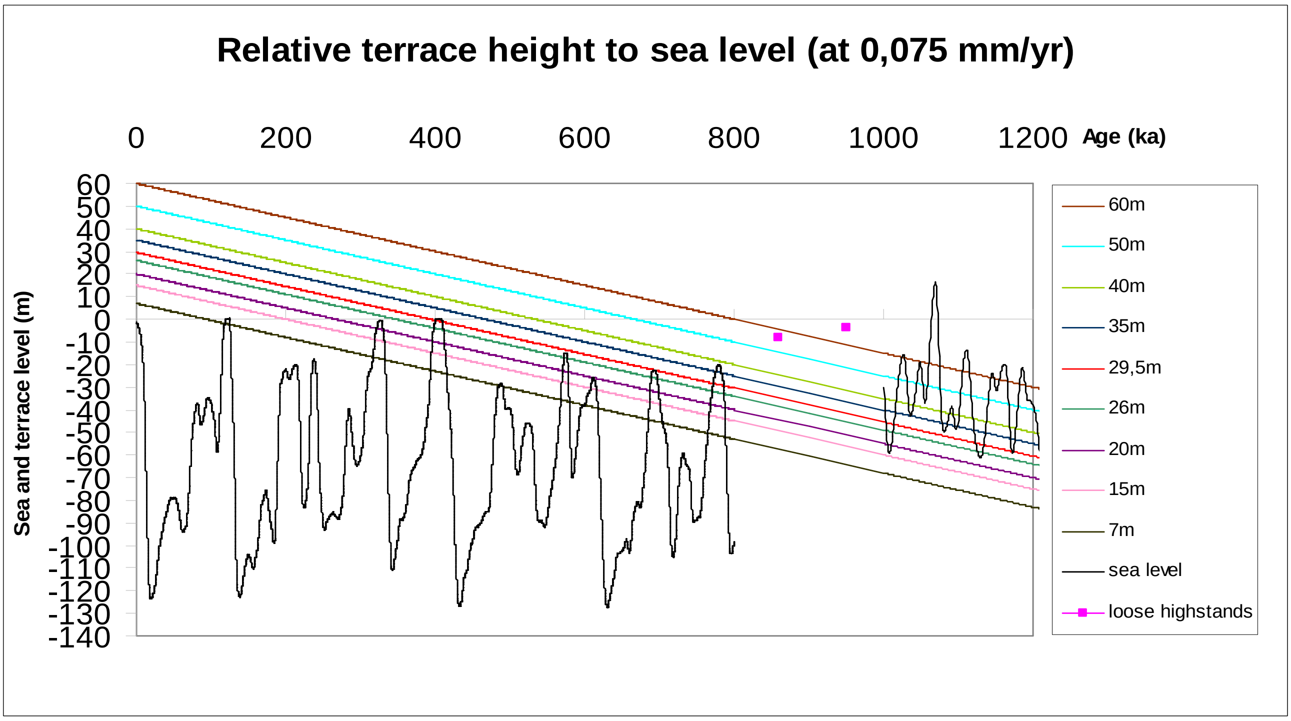

Figure 17: Comparison of terrace level with past sea level at an uplift rate of 0,075 mm/y
The lines show the correlation between the different terrace levels and sea level high-stands.
(Source sea level data: Bintanja et al., 2005; Bintanja and Van de Wal, 2008 in de Boer et al, 2010; Lisiekci and Raymo, 2006)

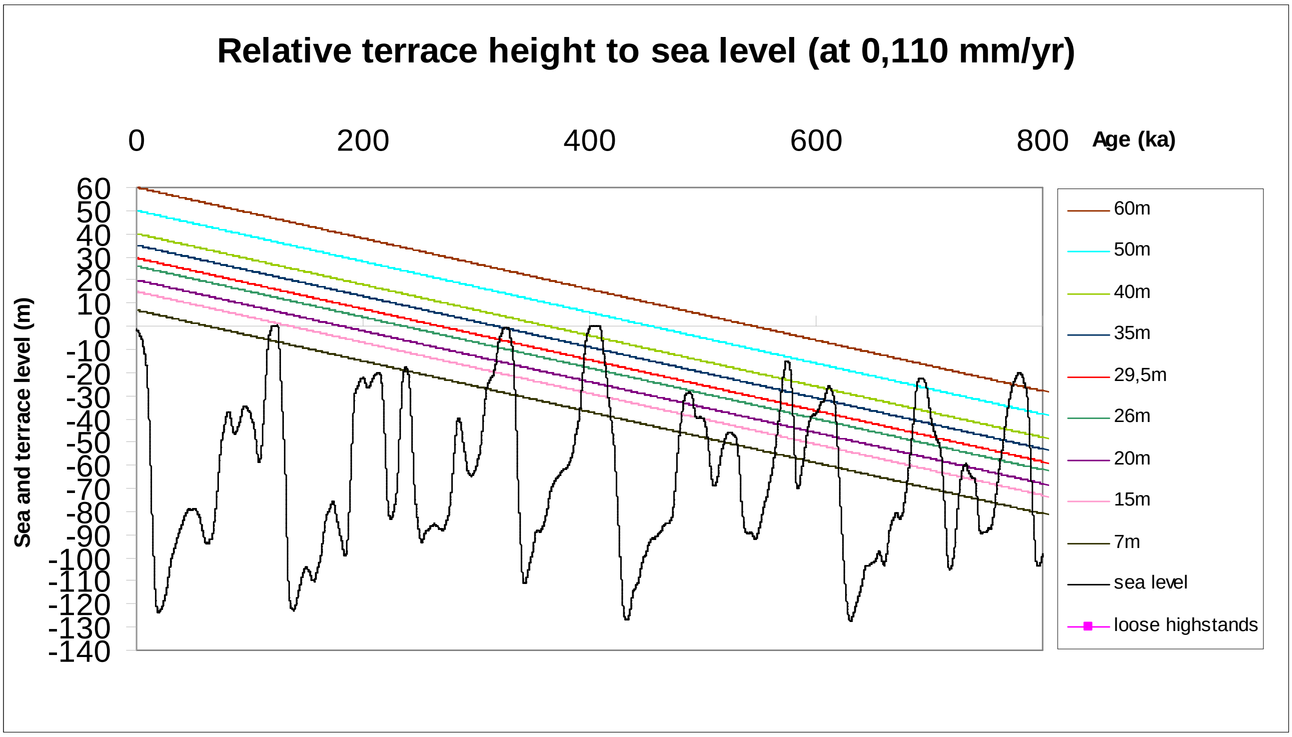

Figure 18: Comparison of terrace level with past sea level at an uplift rate of 0,110 mm/y
The lines show the correlation between the different terrace levels and sea level high-stands.
(Source sea level data: Bintanja et al., 2005)

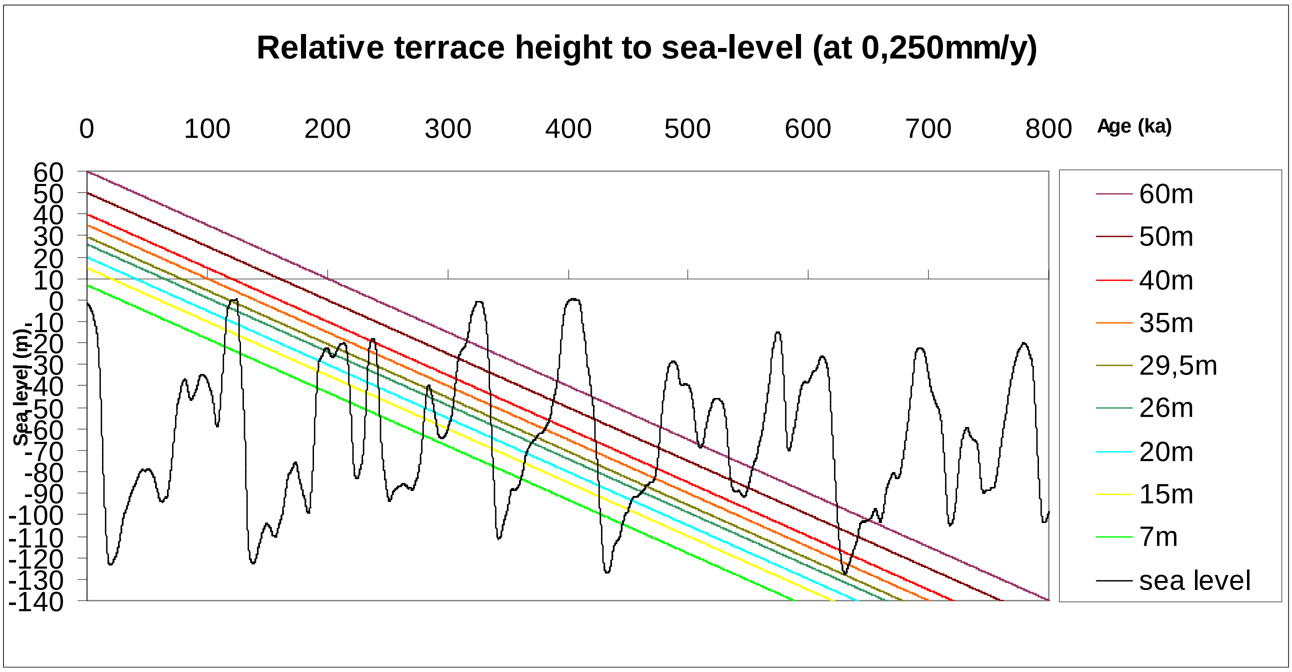

Figure 19: Comparison of terrace level with past sea level at an uplift rate of 0,250 mm/y
The lines show the correlation between the different terrace levels and sea level high-stands.
(Source sea level data: Bintanja et al., 2005)

If we assume a stable uplift rate, at a low uplift rate (0,0528 mm/y) (fig. 15) the lower terraces up to 20 m have a match, just as the 40 and 50 m terrace. The 26 m, 29,5 m, 35 m and 60 m terrace do not show a match with the sea level curve.
At a slightly higher uplift rate, the results do not improve very much. At 0,075 mm/y (fig. 17), the 7 m, 20 m, 30 m, 35 m, and 60 m match with a sea level high-stand. At 0,110 mm/y, the 15 m, 35 m, 40 m, 50 m and 60 m show a match.

If we increase the uplift rate, to an uplift rate of e.g. (0,517 mm/y, fig. 16), (0,250 mm/yr, fig. 19) it is noticed, that most terrace levels meet with the sea level curve during regression or transition periods, but not during sea level high-stands.
From the different graphs can be concluded that it is impossible to find a sea level high-stand for every terrace level at a constant uplift rate. The best results are obtained, with a low uplift rate, between 0,0528 and 0,110. However, even these scenarios still leave many terrace levels which were found in the field, unexplained.

The fact that not every sea level high-stand results in terrace formation in this analysis has to do with the differences in the sea levels during the inter-glacial periods. Differences between high-stands up to 40 m can be found (- 20 to + 20 m, see fig 17), which makes it impossible to find a corresponding terrace level for every sea level high-stand. The difficulty of matching terrace levels beyond 1 Ma will increase, as the sea level fluctuations were closer together (Miller et al., 2005) as can be seen in figure 15. The differences in sea level high-stands still occur, which means that a more fluctuation in uplift rate is will be needed to find a match between terrace levels and high-stands.

5.5.2.5 Terrace formation with a constant uplift rate and age control

Viveen et al. dated OSL- and Berilium-10 samples in the deposits of the Miño terraces at Furna (Portugal, 15 km upstream of the Rosal valley) and Goian (Spain, 8 km upstream of the Rosal valley), respectively a 16-20 m and a 42 m terrace. It is assumed these deposits are equivalents of the 17 m and 40 m terraces along the coast and in the O Rosal valley, as the river does not have a steep gradient between Furna and Goian. In 2009 the OSL samples were taken and analysed, and in 2010-2011 ^{10}Be samples were taken and analysed. The first results of the OSL analysis show that the deposit at Furna has a minimum age of 210 ka in the middle, and 176 ka on the top of the deposit; while the newer analysis show a minimum age of 500 ka. The possible minimum ages of the deposit at Goian lie closer together, and show an age of 506 ka (± 98 ka) for the OSL and a minimum age of 400 ka the ^{10}Be analysis.

During this analysis the first available dates of the Furna and Goian deposit (respectively minimum ages of 176 ka and 210 ka, and 400 ka and 506±98 ka) were used. These do correspond with the idea mentioned above that the deposits have been formed during transitions around inter-glacial periods. If these results are correct the Furna deposit is formed during the transition from glacial MIS 8 to inter-glacial MIS 7 and the transition from inter-glacial MIS 7 and glacial MIS 6 (approx. 200 ka). The Goian terrace would be deposited at the turn from inter-glacial MIS 10 and glacial MIS 11. At the found ages, also peaks in rainfall can be found (Sanchez-Goñi and Desprat, 2005), as can be seen in figure 20. Probably the deposits are incised shortly after their deposition, when the sea level dropped dramatically during respectively MIS 6 and MIS 10. Figure 20 shows the corresponding rainfall peaks around these inter-glacial periods.

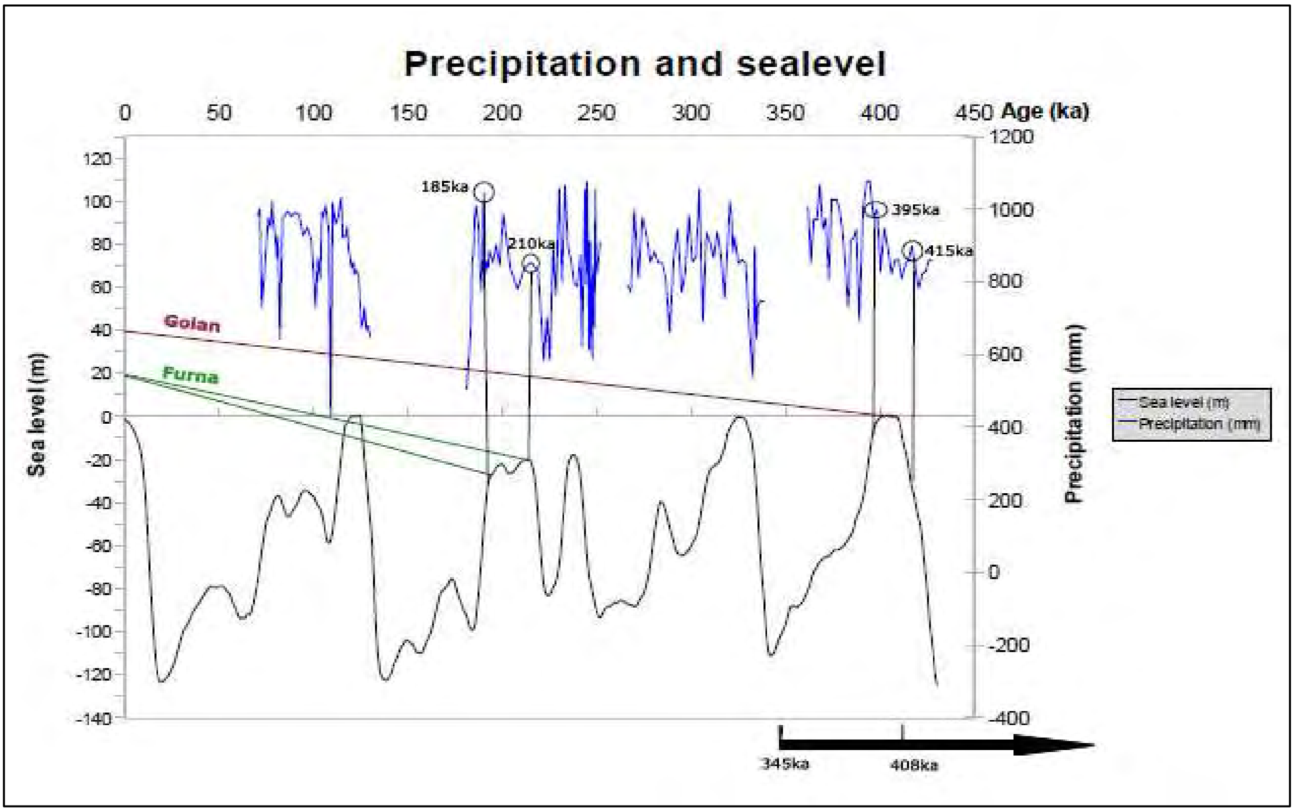

Figure 20: Sea level, precipitation and possibly important events for the Furna and Goian deposits
The lines show the correlation between the different terrace levels and sea level high-stands.
(Source sea level data Bintanja et al., 2005; Precipitation data: Sanchez Goñi and Desprat, 2005)

If we extrapolate this information to other terrace levels, we can also add the 29,5 m terrace at ± 320 ka, (MIS 9), the 26 m terrace at 240 (MIS 7,5) and the 7 m terrace at 125 ka (MIS 5). Also around these points peaks in rainfall can be seen during the transition from inter-glacial to glacial, and smaller peaks during the transition from glacial to inter-glacial. This extrapolation to other levels is shown in figure 21.

It does sound like a logical thing to do but as can be seen in figure 21, the steepness of the different lines is not the same. This means, that if all the terraces are formed during the different high-stands, the uplift rate increased quite a lot between 300 ka and 125 ka. If we take the highest terrace altitude of Furna for the first transition at 210 ka (20m), we end up with a difference in height of 40 m over 210 ka, which leads to an average uplift rate of 0,19 mm/y. If we do the same for the deposit at Goian (terrace height 42 m, age +/- 410 ka, sea level 0) we end up with an average uplift rate of 0,102 mm/y, almost half of which is found at the deposit of Furna.

Newer OSL-dating results give a minimum age of 500 ka to the Furna deposit. This correlates with the very weathered gravels in the Miño deposits (see chapter 5.6.2) and brings forward the idea that the gravels are perhaps deposited by a paleo Miño, rested a while and were incised later. This means that instead of looking for a deposition and erosion phase, only an erosion phase is needed as the deposition is probably very old.
If the old deposits have been incised, more or less like a strath terrace, still younger gravels on top of the terraces are expected. This is not the case except for some granite and gneiss gravels on T1. The absence of easily weatherable gravels suggests that either the terrace incision took place a long time ago and the gravels have disappeared, or it happened so fast no fresh gravels were deposited on top of the terraces.

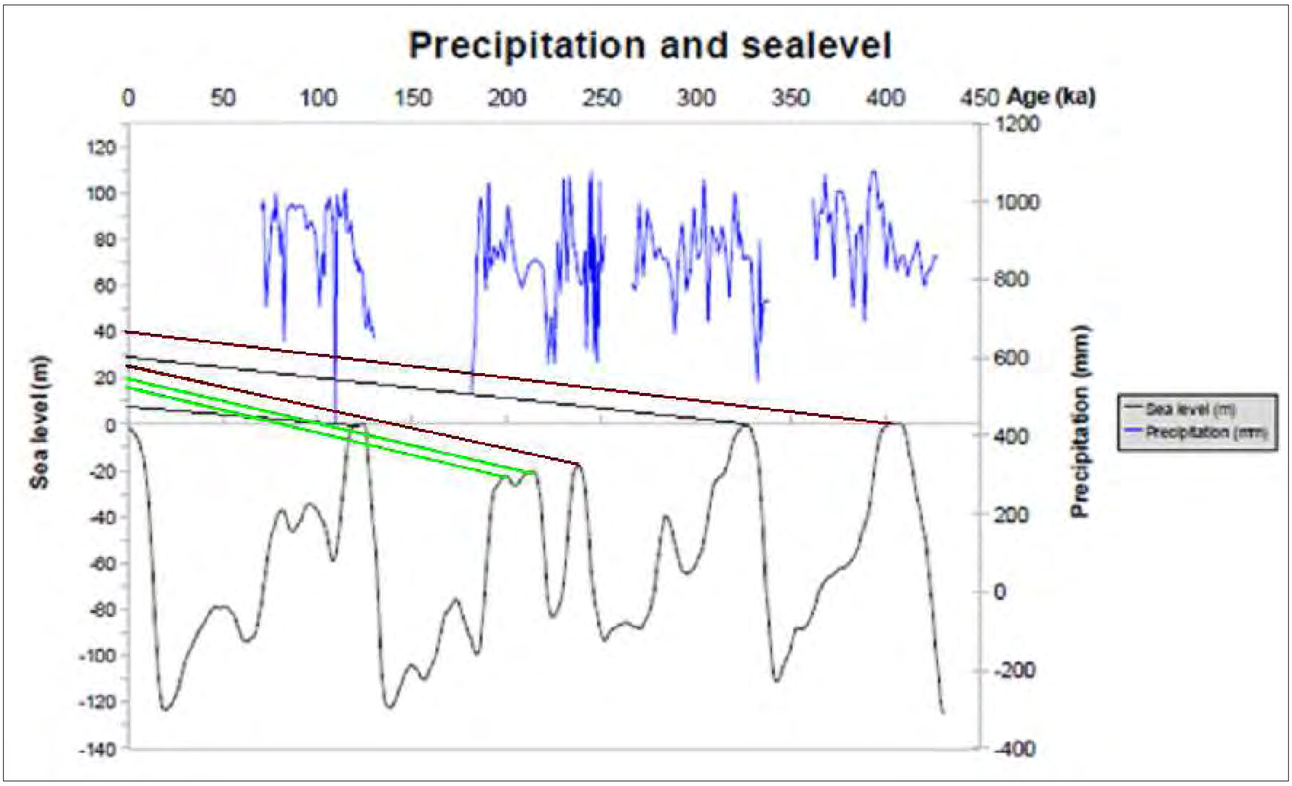

Figure 21: Different terraces formed during different high-stands
The lines show the correlation between the different terrace levels and sea level high-stands.
(Source sea level data: Bintanja et al., 2005; Precipitation data: Sanchez Goñi and Desprat, 2005)

5.5.2.6 Variable uplift rate

From the analysis done in the last two paragraphs it seems plausible that the uplift rate has not been the same over the last 1200 ka. The best results were found with a small uplift rate, but also that analysis could not explain every terrace found in the field.
It is seems illogical the sea level has risen above an already formed terrace, because then new deposits would have been laid down on top of the old deposits and after new incision the old terrace scarp would not be visible anymore. It is possible that the incision temporarily stalled, for example due to sediment influx from above (Schumm and Parker, 1973), or a small change in climate created a terrace. However this would only explain fluvial terraces possible for terrace levels which have not been found along the coast.

In this paragraph some possibilities are discussed with variable uplift rates. First an analysis is done with an average variable uplift rate (1). And secondly an analysis is performed on where the variability in uplift rate is taken over time (2).

(1) Variable uplift rate

In this case the average uplift rate is around 0,055 mm/y, and only the 7 m, 15 m and 20 m, 26 m terrace are formed during the last 800 ky. Respectively during MIS 5e, MIS 9, MIS 11 and MIS 19, all the higher terrace levels are older. See figure 22 .

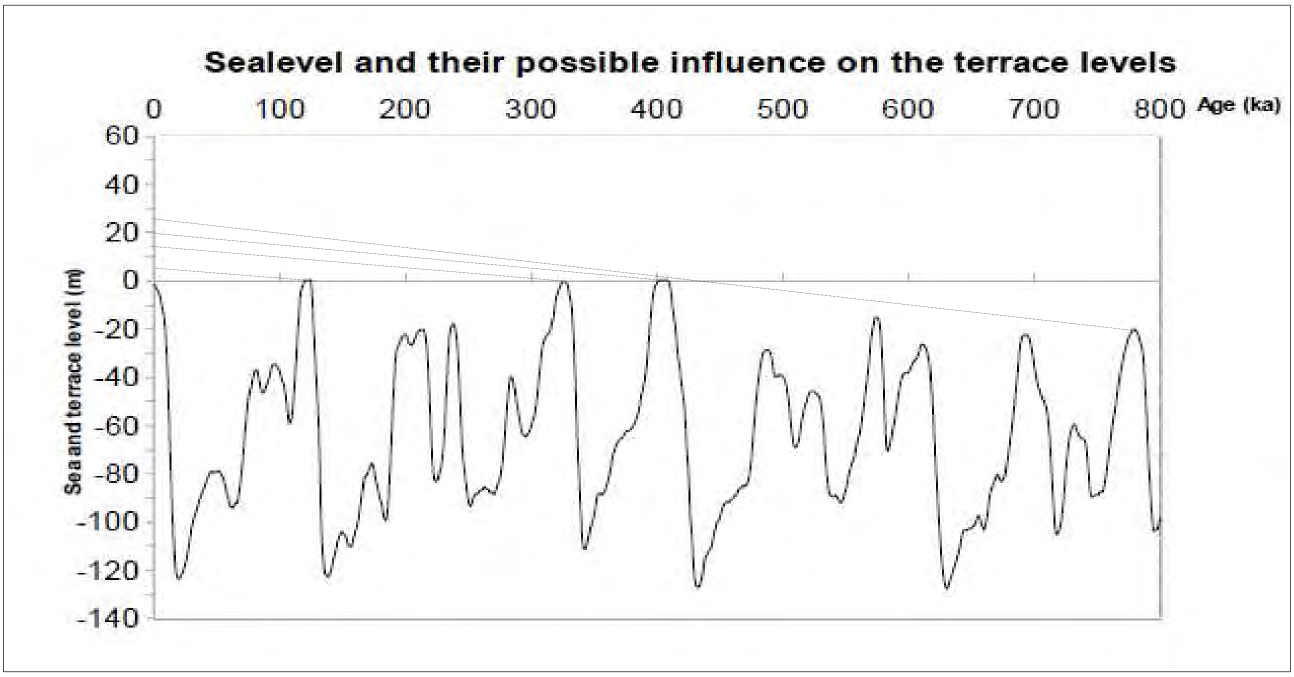

Figure 22: Possible terrace formation with a low uplift rate
The lines show the correlation between the different terrace levels and sea level high-stands.
(Source sea level data: Bintanja et al., 2005

The arguments for this is case are the lack of easy weatherable and fresh gravels on the higher fluvial terrace levels, the lack of scientific information on uplift in the area, as large uplift rates probably would have been noticed and investigated. Though we stay with the same problem as we have with the constant uplift rates: Many prominent high-stands are simply skipped, and that the older terraces do not find a matching sea level high-stand.

(2) Uplift rate taken variable over time

If we take the uplift rate variable many scenarios are possible. As is assumed that the marine and fluvial terraces are formed in the same time, the highest terrace should be the oldest and as the terraces are situated in the same tectonic area, the uplift rate should be the same for every terrace level for the same period of time. Therefore the slope of the lines connecting the terrace levels with the sea level high-stands should be parallel. This method is explained by Burbank and Anderson, (2001) and for instance used by Merrits and Bull (1989).

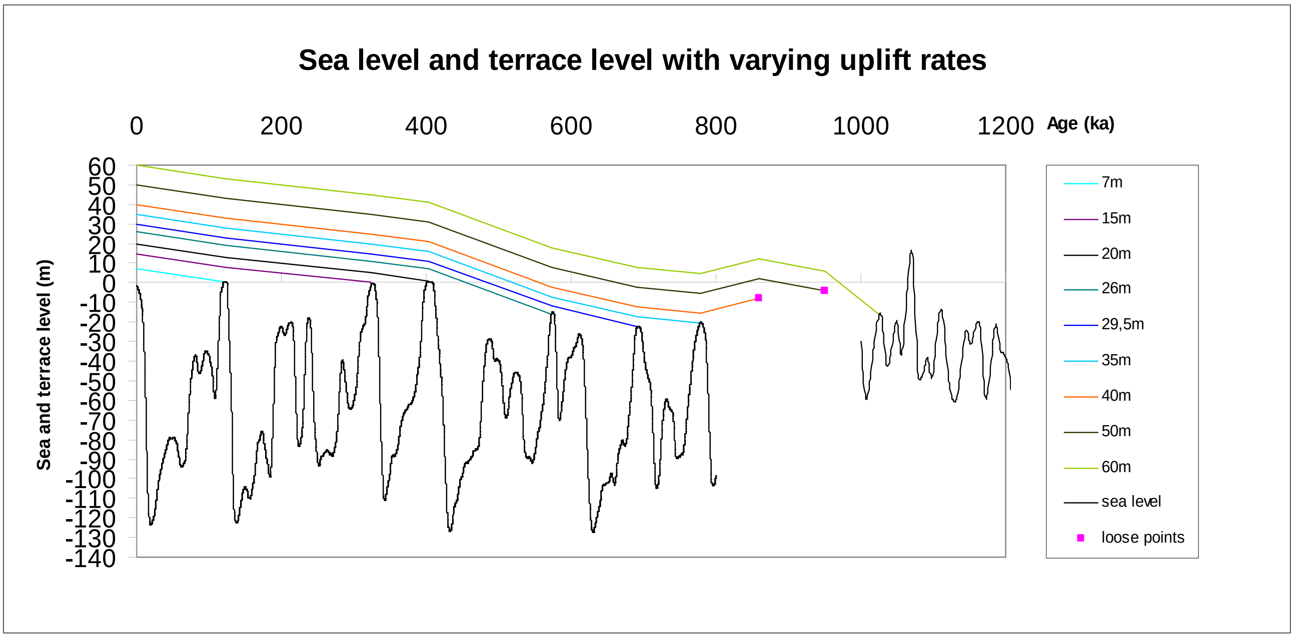

Figure 23: Possible terrace formation with a varying uplift rate
The lines show the correlation between the different terrace levels and sea level high-stands.
(Sea level data Bntanja et al., 2005; Precipitation data: Sanchez Goñi and Desprat, 2005)

In the analysis shown in figure 23, it was tried to match every terrace level with a sea level high-stand (Bintanja et al. 2005; Bintanja and Van de Wal, 2008 in de Boer et al, 2010; Lisiecki and Raymo, 2005), without subsidence being necessary to find a good correlation. In order to achieve this, the lower sea level high-stands have been skipped (e.g. MIS 7, MIS 13). Would MIS 7 be responsible for a terrace level, there would have been an increase in uplift rate between MIS 5 and MIS 7; and before MIS 7, subsidence would be necessary in order to find a sea level high-stand for the higher terrace levels. However, as can be seen from figure 23, even if the lower high-stands are skipped, still uplift is needed in order to find a sea level high-stand for every terrace.

In this scenario the 7 m terrace is formed during MIS 5e; 15 m terrace during MIS 9; 20 m terrace during MIS 11; 26 m terrace during MIS 15; 29,5 m terrace during MIS 17; 35 m terrace during MIS 19; 40 m terrace during MIS 21; 50 m terrace during MIS 25; and the 60 m terrace during MIS 27, a little over 1 Ma in age. This corresponds with a varying uplift rate between 0,032 mm/y (690 - 778 ka) and 0,13 mm/y (403 – 575 ka); between 778 and 860 ka the subsidence was -0,089 mm/y. The uplift rate to connect the 60 m terrace is 0,29 mm/y; though this point was chosen arbitrarily and therefore not taken into account.

The convincing part of this scenario is that it does not need any extreme uplift or subsidence rates to come to a match. On the other hand it is weird, as also found in earlier analysis, that two prominent sea level high-stands do not seem to have had an effect on the marine terraces, and the dated deposits are older than the preliminary results show (resp. 200 ky older for the 20 m terrace and 500 ky older for the 40 m terrace).

To analyse terrace – sea level correlation with variable uplift rates is it better to take the uplift rate variable over time, rather than using average variable uplift rates. Analysis with variable uplift rates over time gives a better and truer visualisation of the change in uplift rates. Therefore, from here on the analyses are done with the uplift rates varying over time.

5.5.2.7 *Variable uplift rate with age control*

If we allow the uplift / subsidence rate to fluctuate more, take the dated deposits into account and we assume these have been deposited shortly before the terraces were formed we find the graph as can be seen in figure 23.

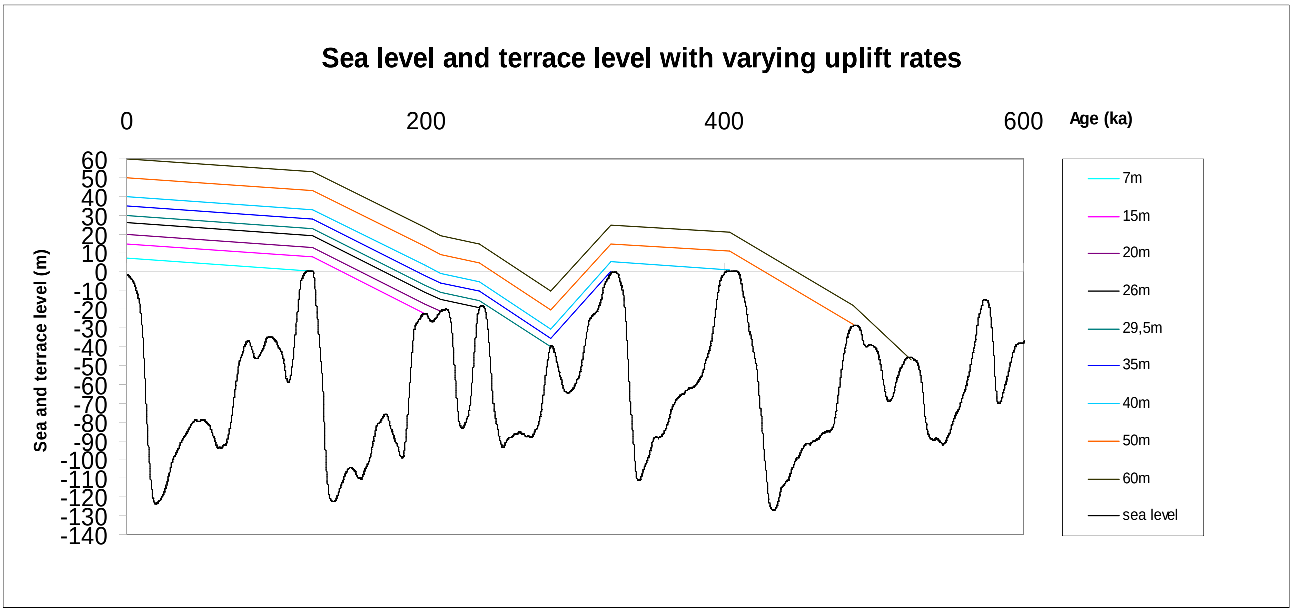

Figure 24: Possible terrace formation with a varying uplift rate
The lines show the correlation between the different terrace levels and sea level high-stands.
(Sea level data Bntanja et al., 2005; Precipitation data: Sanchez Goñi and Desprat, 2005)

As can be seen from the graph (fig. 24) the uplift rate fluctuates more in this graph, and once again uplift, as well as subsidence is needed in order to find a match between every terrace level high-stands. The uplift rate varies between 0,0512 mm/y between 0-124 ka, and 0,63 mm/y between 199 and 210 ka. Between 236 and 283 ka subsidence takes place at a rate of 0,87 mm/y. In this analysis the 7 m terrace is formed during MIS 5e; 15 m, 20 m and 26 m are formed around MIS 7; the high-stands at MIS 9 are responsible for the 29,5 and 35 m terrace. The 40 m terrace is formed during MIS 11, and the 50 and 60 m terrace during MIS 13. Hence the oldest terrace is 521 ka in age.
This scenario does not seem very convincing, since the maximum uplift and subsidence rates are quite high and at least three large switches in uplift rate are needed (respectively at 280, 320 and 400 ka) for which no indications are found in the field or literature.

5.5.2.8 Variable uplift rate and merged terraces

In this last part I investigate the possibility that different terrace levels actually belong together, because they lie at different altitudes due to topographic differences, or because they are covered with colluvium. It is true that most other authors used larger intervals (e.g. Butzer, 1967; Cano Pan et al, 1997; Teixeira, 1952), and that large parts of the marine terrace sequences, especially on the Spanish side are covered with colluvia (Blanco Chao et al., 2002; 2006). However in the analysis only the larger most reliable levels, which had corresponding terraces at other locations have been taken into account.

Possibly one can connect the T2b and T3a terraces to each other because they lie next to each other rather than above each other along the coast. In that case a range from 14-25 m is obtained

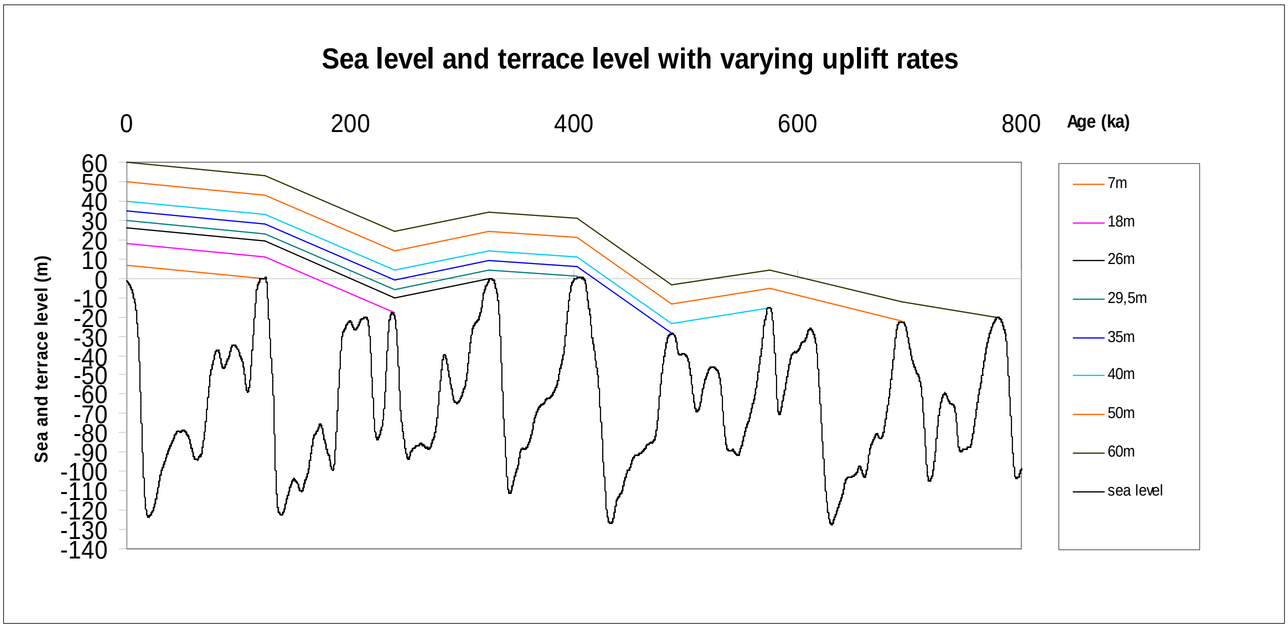

Figure 25: Possible terrace formation with T3a and T2b merged and variable uplift rates
The lines show the correlation between the different terrace levels and sea level high-stands.
(Sea level data Bntanja et al., 2005; Precipitation data: Sanchez Goñi and Desprat, 2005)

The last scenario has less extreme uplift rates, though they are still between 0,052 (0-124 ka) and 0,41 mm/y (401-487 ka); and the subsidence rates between 0,089 (487-575 ka) and 0,11 mm/y (240-323 ka).

5.5.2.9 Variable uplift rate and merged terraces with age control

If we combine the possibility of a varying uplift rate with the 15 m and 20 m terrace merged, and assume once again the terraces on top of the dated deposits are formed shortly after their deposition (the 18 m (15-20 m) terrace around 200 ka, and the 40m terrace around 400 ka. we find the following graph (figure 26).

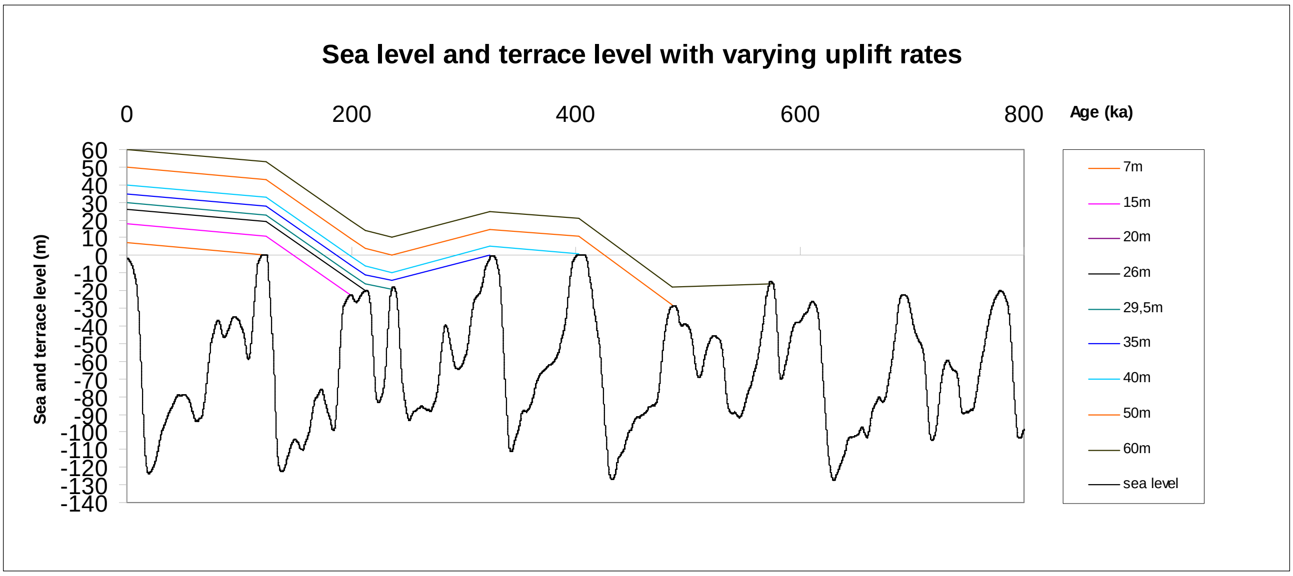

Figure 26: Possible terrace formation with T3a and T2b merged; variable uplift rates and dated deposits taken into account. The lines show the correlation between the different terrace levels and sea level high-stands. (Sea level data Bntanja et al., 2005; Precipitation data: Sanchez Goñi and Desprat, 2005)

Merging of terrace levels does not change a lot in the terrace level- sea level high-stands correlation, though it flattens the uplift rates to some extent. The uplift rates vary between 0,052 (0-124 ka) and 0,46 mm/y (403-487 ka) and the subsidence rates between 0,02 (487-575 ka) and 0,17 mm/y (240-323 ka). This is a lot less than maximum average rates of 0,67 and 0,87 mm/y.

In this scenario the 7 m terrace is formed during MIS 5; the 18 m, 26 m and 30 m terrace during MIS 7; the 35 m terrace during MIS 9; 40 m terrace during MIS 11 and the 50 and 60 m terrace during MIS 13 and 15 respectively.

It is incorrect to change the found field data in order to find better results. But this experiment shows that even with the neglection of terrace levels, the trend of the sea level – terrace correlation does not change dramatically. Though it smoothes the uplift rates some what, especially when we take dated deposits into account.

5.5.2.10 Remaining terraces

The analysis in the last paragraphs shows possible formation for the T1a, T2a, T3a, T3b, T4a, T4b, T5a, T6a and T7. As mentioned in chapter 5.1 and 5.2, the other found marine terraces are probably terraced or overlain by colluvia. Colluvial deposits on top of marine terrace levels have indeed been found along the Spanish and Portuguese coast (Butzer, 1967; Cano Pan, 1997; Meireles and Texier, 2000).

The fluvial T1a (4-5m) and T5b (45-48m) are probably formed by changes in climate. The T5b is probably formed after the T6a was incised. During climate change from inter-glacial to glacial, first the T6a was incised, but deterioration in climate lead to more sediment influx, temporarily blocking the channel, stalling further incision (Tebbens et al, 2000; Stemerink et al., 2010; Schumm and Parker, 1973). As base level continued to drop, incision continued, and also the newly deposited sediments were incised, leaving a T5b terrace just below the T6a level.

The T1a is probably very young of age, and formed during the transition from the last glacial to the present situation. The change from glacial to inter-glacial, caused a higher discharge and sediment availability, which in combination with a rising base level lead to deposition. After the climate stabilised, cleaner water flowed through the Miño and the terrace was incised, leaving it 4-5 m above the present Miño.

The wetland and the islands in the Miño are believed to be very recent of age, and are possibly deposited right now. Their soil seems to consist of the same particles presently carried by Miño, at the O Rosal valley. And the size and shape of the wetland and islands seem to have changed recently, when aerial photographs (1984) and satellite images (Google Earth, 2010) are compared.

5.5.3 Discussion

Results analysis

From the different scenarios shown above, can be concluded that probably the uplift rate is not stable. If it would be stable, the best results are achieved with a very small uplift rate (0,0527 mm/y), though many terrace levels are left unexplained. In order to find a sea level high-stand for every terrace, it is necessary to incorporate uplift as well as subsidence in the analysis. Especially if it is believed all mayor sea level high-stands lead to the creation of a terrace.

Taking varying uplift and subsidence rates into account, every match between a terrace level and a sea level high-stand is possible. If we take the minimum ages of the dated deposits as fixed ages, then the uplift rate fluctuated strongly in the study area in the end of the Quaternary(fig. 24), even if we merge two terrace levels (fig. 26). With merged terrace levels the uplift rate would still range between (-0,87 to 0,63 mm/y).
Because the ages of the dated deposits are not certain (minimum ages, deposition not necessarily the same age as terrace formation, different results). A conservative approach with slow uplift and subsidence rates and few harsh transitions seems therefore to be the most convincing solution, as shown in figure 22. This scenario has uplift, rates ranging between -0,087 and 0,13 mm/y respectively places the terrace formation of the highest, 60 m terrace, a little over 1 Ma in age. Although this means the dated deposits are at least respectively 200 ky and 460 ky older than found in the OSL and ^{10}Be dating, and prominent lower sea level high stands (MIS 7, ± 200 ka; and MIS 13, ± 500 ka), have not been taken into account because they would have increased the uplift and subsidence rates a lot.

It has not been investigated how the uplift curves would look if the terraces would have been formed before 1100 ka, however in order to find a match between sea level curve and terrace level, the uplift – subsidence rate would have had to fluctuate even more to find a match than during the last 1100 Ma.

The possibility exists some levels are formed during the same inter-glacial but differ in height due to colluvium lying on top of the terrace level. Therefore some terrace levels were merged together in the analysis. This does not change the general picture, it only makes the age of the terraces a bit younger, and smoothes the uplift and subsidence rates when the dated deposits are taken into account. However, as a selection of the most reliable terraces already had been made before this analysis, it is believed a more conservative scenario is more convincing, which means the highest terrace is a little over 1 Ma in age. This is in correspondence with the very weathered gravels found in the study area (Repka et al., 2007; Howard et al., 1995).

Fluvial terraces T1, T2b, T3a, T3b, T4a,T5a, T6a and T7 are formed during the incision occurring after the same high-stand which formed the marine terraces. Fluvial terraces T1a and T5b have probably not been formed during an inter-glacial as their altitudes do not correspond with levels along the coast. These terraces are probably formed during periods of climate change or river capture. If the terraces are very old of age, it must be noted they have been preserved well, still terrace scarps can be identified even older terraces, possibly >800 ka in age. A possible explanation for the preservation is the thickness of the deposits in combination with very good infiltration of the gravel deposits (Tebbens and Veldkamp, 2001).

A large problem with this analysis is that it is lacks certainty, and is based on many assumptions. First of all, it is not sure what the uplift rate in the area is, if it is constant, or changing over time. The terrace heights seem to correlate really well, but possibly the blocks did move relative to one another, and the similarities in altitude are just a coincidence. Because we do not know a reliable age of the terrace levels, it is hard to prove the correlation. At last the sea level curves are global curves based on $\delta^{18}O$ data, which do not always exactly correlate with data found in the field (Hearty et al, 2007).

Methods & Data
The biggest problem with allowing varying uplift rates in the analysis, is that almost every scenario is possible. As Burbank and Anderson (2001) already mentioned: "If one permits the uplift rate to vary without a constraint (…) a perfect, but probably meaningless, match can always be obtained" (p. 177). To prevent this problem, most authors doing research on marine terraces indeed used a stable uplift rate to match their terrace levels with sea level high-stands (Tellinghuisen; Valensise and Ward, 1991), or had more constraints to the uplift rate.

However in these analyses the results with a stable uplift rate are really poor. Other researchers however did either not find many terraces (Alvarez-Marrón et al, 2008) or were working in an area with more prominent uplift (Kennedy et al., 1981; Merrits and Bull, 1989; Tellinghuisen; Valensise and Ward, 1991). In areas with more prominent uplift, the steps between terraces are higher and consequently it is easier to match terraces with sea level high-stands which lower than other sea level high-stands.

There are few constraints which can be taken into account when a variable uplift rate is investigated. Some deposits have been dated, however there are still uncertainties on the reliability of the dating methods as they are relatively new (Tanaka et al, 1997; Lucas et al., 2007; Dickin). The results of the dated deposits give minimum ages, while the deposits are possibly older than the terrace formation. Consequently it does not add a lot to the analyses. It seems probable that the uplift rate has not been high recently, but figures are unknown. Due to these uncertainties it is hard to come to one conclusive solution for this problem.

Also as was discussed in section 5.5.1, it is unclear how high the sea level was exactly, the interpretation differs between authors and the methods they used (Dutton et al., 2009). Different authors, methods and local differences cause some difference in sea level high-stands (Hearty et al., 2007). The data used are based on $\delta^{18}O$ data (Bintanja et al, 2005; Bintanja and Van de Wal, 2008; Lisiecki and Ramyo, 2005), which fails to show temporary variability in sea level high-stands (Hearty et al., 2007; Dutton et al, 2009) and is sometimes an under estimation (Dutton et al., 2009). Still Hearty et al. (2007) conclude the geomorphological records of sea level high-stands are coherent between different regions around the world, which makes it possible to use global sea level curves for specific locations.

5.5.3 Conclusion

From this analysis can be concluded that the study area is probably uplifting, while in the past also periods of subsidence have taken place. The terrace levels have been formed around sea level high-stands. Just before and after the sea level high-stands the Miño deposited sediment in the O Rosal valley. These deposits have taken place due to changes in climate during transition phases to and from the inter-glacial periods, causing more discharge and sediment transport in the Miño. These deposits were incised due to a drop in sea level caused by regressing sea level, which in turn was caused by a deteriorating climate with more water captured in ice, influenced by the Milankovitch cycles. During the stable period of the sea level high-stand the constant erosion formed marine terraces along the coast.

It is not clear when the terraces are actually formed, but due to insecurity of dated deposits a conservative scenario seems, for now, the most convincing. This scenario predicts that the 7 m terrace (T1b) is formed during MIS 5e; 15 m terrace (T2b) during MIS 9; 20 m terrace (T3a) during MIS 11; 26 m terrace (T3b) during MIS 15; 29,5 m terrace (T4a) during MIS 17; 35 m terrace (T4b) during MIS 19; 40 m (T5a) terrace during MIS 21; 50 m terrace (T6a) during MIS 25; and the 60 m terrace (T7) during MIS 27, a little over 1 Ma in age. In this scenario the uplift rate fluctuates between -0,087 and 0,13 mm/y).

The other lower terrace level along the coast (T2a) is probably a T1 terrace covered by colluvia, deposited during the last glacial (Alonso and Pages, 2007); the T8, T9 are explained as man made terraces, while the T10 is probably flattened by slope processes triggered by wood production.

The T5b (44-48 m) and T1a (4-7 m) terraces in the O Rosal valley are formed by changes in discharge and sediment load. Possibly base level drop during the transition from inter-glacial to glacial caused the incision of the T6a, but upwards erosion an increase in gradient and a deterioration in climate lead to more sediment influx, temporarily filling the river channel near the O Rosal valley, and stalling further incision (Tebbens et al., 2000; Stemerink et al., 2010; Schumm and Parker, 1973). As base level continued to drop, incision continued, also the newly deposited sediments were incised, leaving a T5b terrace just below the T6a level and the T1a below the T1b.

In this scenario the deposits at the 20 m and 40 m terrace are at least 400 ka and 860 ka in age. This is in agreement with the lack of easy weatherable gravels higher than 20 m. However it is a lot older than the first results of the dated deposits. The fact that the terraces, especially along the Miño are preserved very well is possibly due to the thick deposits and good infiltration.

5.6 Interpretation of indications in deposits

In this section I discuss the structures which were found in gravel deposits in the O Rosal valley, and propose possible solutions for the different structures.

5.6.1 Sediments in the large exposures

Two kinds of exposures are present in the area. Firstly, exposures of quartzite and quartz gravels, up to more than 7 meter high. And secondly, exposures of messy deposits, with angular quartz and pieces of granite, often in a dark brown soil, and sometimes also containing some quartz or quartzite gravels. Although both kinds of deposits occur often in the study area, I will only focus on the gravel deposits. These are thought to be fluvial deposits, while the second kind of deposits are probably local slope deposits which contain less information about the general landscape genesis of the O Rosal valley.

From the highest to the lowest most important gravel deposit: O Rosal (50 m), A Cunchada (45-49 m), A Cumeira de Abaixo (41 m), As Medas (40 m), LIDL (20 m) and the small incised creek at the construction of the new highway, south of A Cumeira de Abaixo (8 m), from now on referred to as the highway exposure. An indication of the location of these deposits is given in figure 5.10, the highway exposure is just south of A Cumeira de Abaixo, at the incised creek.

5.6.1.1 O Rosal – 50m

At the cemetery of O Rosal an exposure is found of well weathered quartz and quartzite gravels which are locally strongly cemented by orange-brown oxides, probably iron oxides. The gravels have an average size of 4 centimetre. The exposure has a minimum height of 6,5 meter. The actual depth of the deposit is not known, since hardrock is not met. The area of the deposit is 50.000 m^2. An imbrication of 200° SSW can be seen and straight lines in the exposure seem to be dipping towards the NNW at 345°. This could point to tectonic tilt of the deposit.
This deposit is probably the most eastern deposit, on the 40 m terrace to the east gravel has not been found any more.

5.6.1.2 A Cunchada and Manuel Suarez - 45-49m

Near A Cunchada three exposures are found. One in the west at the border of A Cunchada and San Dian, one in the east facing the highschool Manuel Suarez and one behind the sporting facilities along the PO-354. These exposures are discussed together since they most probably are exposures of the same deposit. The exposures lie close together, some 300 meter apart. They lie more or less on the same altitude, the composition of the gravels does not seem to differ and at both exposures the same properties are found. The gravels are similarly weathered and concreted as the gravels found at O Rosal. They have a composition of 70 % quartzite and 30 % quartz of around 4-5 cm.

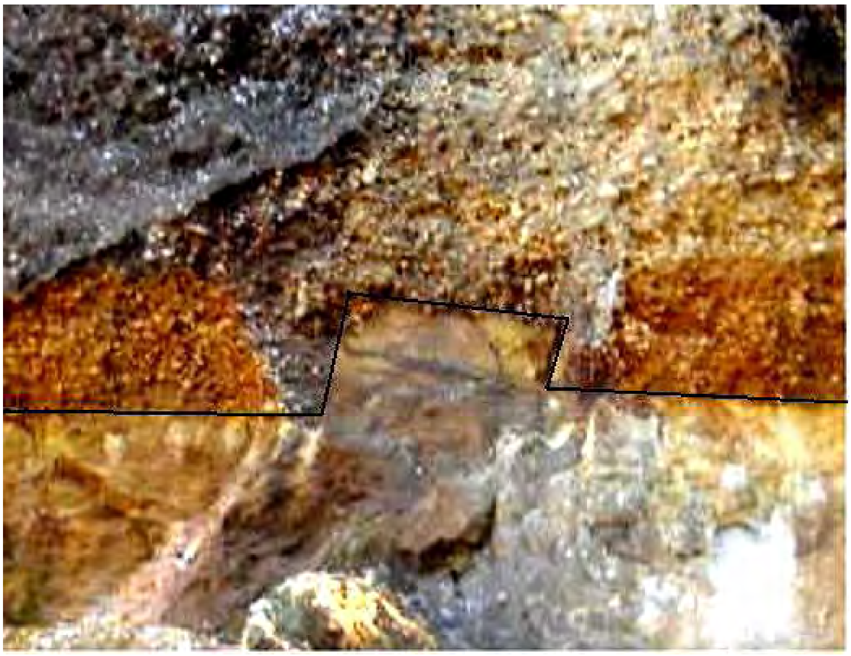

Figure 27: Angular bump in sapprolite beneath the gravel deposit in A Cunchada

The exposure at San Dian is a roadcut. It has a height of 2,5 meter on top of schist-sapprolite, and at some places a up to half a meter of dark brown soil lies on top of the gravel deposit. The gravels show a very convincing imbrication towards 210° SSW. This is the most western gravel deposit in PART I, less than 100 meter to the west only sapprolite and angular quartz are found.

The exposure at the high school Manuel Suarez is a quarry and has a height of 6,30 meter on top of sapprolite. Also here the imbrication is SSW and fluvial structures are identified. It is interesting that the top of the sapprolite is not flat, but has an angular block sticking out of +/- 40 cm high and 1,20 m wide. This bump was also found back in the sapprolite at the exposure at A Cunchada with practically the same dimensions..
It is investigated whether edges of the block continued into the sapprolite. There seems to be some difference. However due to the very weathered state of the hard rock, it is uncertain whether these are actual break structures or coincidental variation in the hardrock caused by water seepage or other processes. In case it is not a small fault, it is a peculiar bench of resistant schist going from 70° E - 250° W (shown in fig. 27). The third exposure shows 3,5 meter of quartzite and quartz with sandy layers in it. The bottom is not visible.
The area in which these three deposits lie does not have a clear boundary to the south, but when these three exposures are connected the area is around 190.000 m^2 in size.

5.6.1.3 A Cumeira de Abaixo – 40m

At A Cumeira de Abaixo an exposure is found of 4 meter high, with around 60% quartzite and 40% quartz gravels. All gravels are very weathered and brown and purple oxidation marks are visible in the profile. Possibly iron. The average size of the gravels is around 3 cm up to a maximum size of 15 cm, and the roundedness of these gravels is comparable with the roundedness of the gravels found at other exposures. The exposure shows an imbrication of 140° SE. The bottom of the deposit is not visible. Close by (respectively 50 m south and 50 m east), at two other locations also gravel exposures are found. If we assume these are part of the same deposit the total height of the deposit is at least 10 meter. Connecting all the found exposures which are presumed to be part of this same deposit comes to an area of around 60.000 m^2.

5.6.1.4 As Medas

At As Medas several exposures have been found, on all sides of the hill exposures are present where gravel is visible. The highest exposure is 7,2 meter high, though the bottom is not reached. The hardrock is visible on the northern, and on the south-eastern side of the hill at around 40 meter. To the northwest the gravel abruptly disappears and only sapprolite with a thin soil on top is found. The exposures on the southern side show sediments as deep as 31 meter, the base of the deposits is not found. The gravels found at As Medas compose of very weathered quartz (25%) and quartzite (75%), locally strongly cemented with an orange dark brown, purplish colour. Most possibly caused by iron oxides. The gravels are rounded with an average size around 5 centimeter, with a maximum of 12 centimeter. Five different exposures are visible at As Medas. I will discuss the three I think are most interesting.

House Exposure

On the southwest of the road going through As Medas behind a house an exposure of 6 meter high is present. This exposure shows straight lines in the profile dipping 280 ° west under an angle of 10-20° to the horizontal. This is the same kind of structure as is found at O Rosal. In figure 28 a picture shown. A possible imbrication of 150° SE is seen in the exposure as well.

Figure 28: Straight layers dipping towards the right(west) in As Medas

Broken Quartz-vein
A second interesting exposure lies on the south eastern edge of the hill of As Medas. It has more or less the same base as the former exposure. This exposure is a wall of 50 meter long running South West-North East.
To the SW side the gravel exposure is around 2,5-3 meter high and does not show its base. It dips 230° to the SW, and shows an imbrication of 150° SE. From the middle of the exposure to the north eastern side, the total height goes up to 5,5 meter. In this part 1,7 up to 2,3 meter of sapprolite is visible beneath the gravel deposit. In the sapprolite a quartz-vein is shown which is broken into three pieces.
The broken quartz-vein implies that the sapprolite has been under pressure at one point in time. Two possibilities arise. Or the sapprolite has risen in the exposure, causing the vein to crack. Or the pressure was applied before the deposition of the gravel, and the fact that the sapprolite lies higher in the deposit is because it is coincidental more resistant.

River channel
The third exposure at As Medas lies on the most southern edge of the hill. It is the exposure which has the lowest base, around 31 meter altitude. The exposure is 3,5 meter high and the base of the deposit is not visible.
The lower layer of the exposure is heavily cemented angular quartz, on top of this to the west lies a gravel deposit and to the east an former stream channel is visible. The stream channel is about 4 meter wide and shows different phases. Sand and gravel layers are alternated, and the river channel seems to be moving towards the south-east.
This exposure shows an imbrication of 130° -150° SE, a possible dip towards 200° SW.

Summary As Medas
From the five different exposures a few things can be concluded. The difference in height from the lowest exposure to the highest top is 9 meter, however the base and top of the exposures in the south is lower than in the north. In most exposures the gravel deposits are dipping. The combined direction in which the deposit dips is 240° SW and the combined imbrication is 150° SE. The hardrock at As Medas has at one point been under pressure, cracking the quartz-vein. The combined area of As Medas is 87.000m^2.

5.6.1.5 LIDL- 17m

The exposures at the LIDL, lie along the PO-552 behind the LIDL. The deposit has two exposures. The first one is 5 meter high and shows 1 meter of gravel on top of 4 meter of sapprolite; more to the east another exposure is visible which is three meter high. The base of the deposit is not visible here. The gravels are composed of quartzite and quartz, they are not that powdery as in the other three exposures, although still weathered. The exposure does not show any structures.

5.6.1.6 Highway – 8m

The lowest found gravel exposure lies at the construction of a new highway, south of A Cumeira de Abaixo.. The total gravel exposure is 2 meter high, consists of fresh quartzite (50%) and quartz (50%) with an average of 7 cm and hardly weathered. Structures are not visible in the exposure.
The original top of the gravel deposit is not quite sure as colluvium is lying on top and the deposit is situated in the valley of a small creek Higher up the slope also gravels are found, to the west, east and south. It is however not thought this deposit has anything to do with the other deposits, as all the other deposits have a base which lies higher and consist of more weathered gravel, and hundred meter north and south of this exposure sapprolite is found up to 5 meter higher.
This deposit lies close to three watercourses. The small creek which flows from A Cunchada to the Tamuxe lies at 10 meter, the Tamuxe flows 500 meter to the east and the Miño lies less than a kilometre to the south.

5.6.2 Discussion of the large deposits

5.6.2.1 Depth

The exposures have depths up to 7,2 meter high. Though often the base of the deposit is not visible, and lower exposures sometimes suggest a deposit bigger than 10 meter. It is however hard to give an average depth of the deposits, since contrasting information has been found. At A Cunchada the deposit shows sapprolite at 6,7 meter deep from the top of the deposit; at As Medas sapprolite is found on the south eastern and north western side, however all the other gravel exposures do not show the base of the deposits. At the LIDL exposures sapprolite is found below 1 meter of gravel to the west, while the base of the deposit is not visible on the eastern side. At the highway exposure, gravel lies at least as deep as 6 meter. However, north and south of the exposure sapprolite is found up to 10 meter.
It can be concluded that not all terraces have the same deposit depth. The depth of the deposits even differs within a terrace level. The base of the deposits is not flat, but consists of depressions and higher parts.
In the western part of the catchment the boundary of the gravel is found at San Dian and west of As Medas.

5.6.2.2 Composition, Size, Weathering and Dating

At all exposures the gravel that was found was very weathered. At the moment Viveen et al. are working on a research in which the size, composition and roundedness of the classes between the different gravel deposits in the Miño valley are compared. Also in the O Rosal valley samples (500 pcs.) have been taken at O Rosal (50 m), As Medas (40 m) and the LIDL-exposure (17 m). The samples show that the 40 and 50 meter terrace are almost similar in composition and size, and the LIDL exposure contains relatively more quartz and contains smaller gravels. The highway deposit has not been analysed in depth, but does on first sight show more quartz and larger clasts, this is also found in the 15 m terrace in Furna (± 15 km upstream) (Viveen, personal communication, 2010). The highway deposit is probably younger than the rest of the deposits, as the gravels are fresh, relatively a lot of quartz is present and a strong matrix is absent.
The deposits below the 40 and 50 meter terrace are very similar, and could be formed by the during the same depositional period. The 17 m deposit contains somewhat smaller rocks, which implies a deposition in a less energetic environment, during another depositional phase. The 8 m deposit by a stream with more energy. However, it is unclear if it is a Miño deposit or a deposit of the small creek coming from A Cunchada.

The gravels at all other exposures are very weathered, to the extent that some can be crushed with bare hands. Often they are found cemented in iron oxide. Only at A Cunchada the gravels are not cemented in iron oxide, here water was seeping out of the exposure.
Quartzite gravels are very resistant to chemical weathering (Repka et al., 1997, Howard et al. 1995) which implies that the deposit in the O Rosal valley is very old. Indeed Howard et al. investigated weathered quartz and quartzite clasts in Virginia, an area which also has a humid, temperate climate like south western Galicia. They found similar properties as present in the O Rosal valley: very weathered quartz and quartzite gravels, absence of easier weatherable gravels and clear iron oxidation marks in the deposits. Though plinthite is not found in the exposes, ferricretion is.

Howard et al., (1995) found that deposits with disintegrating quartzite clasts are 10,8 Ma-13,0 Ma in age in their study area, depending on the amount of disintegrating quartzite clasts. To form quartzite gravels with 'weathering rinds', which the fresher quartzite gravels sometimes have a period of at least 3,4-5,3 My is needed (Howard et al., 1995). These ages are far beyond the time range which is analysed in section 5.5. Howard et al. (1995) mention that small climatological differences can be of large influence, and mention that the deposits they investigated are not recycled. So it is possible that weathering in the Miño valley is more rapid, or that the gravels are recycled from another Miño deposit, further upstream. Possibly different chemical composition of the quartzite could also lead to different chemical erosion rates.
However, gravels, as weathered as we find them in the O Rosal valley (and the Louro valley, Butzer, 1967) can not travel many kilometres without being totally destroyed. Therefore if we assume the gravels are deposited hard, but already with weathering rinds (3,4-5,3 My old) and

chemical weathering is twice as fast in the study area, as in Virginia, this would give a deposit of at least (10,8-5,3)/2 = 2,75 Ma in age. To get a better grip on the exact age of the deposits, Viveen et al. are dating many deposits with OSL and Berilium-10.

5.6.2.3 Age of the deposits

As mentioned in section 5.5.2.4, preliminary results of OSL- and ^{10}Be-dating analyses showed minimum ages of the deposit below the 17-20 m terrace at Furna of 176-500 ka; and 400-500 ±98 ka for the deposit below the 42 m terrace at Goian. The most convincing terrace-sea level correlation leads to minimum ages for these deposits of respectively 420 ka for Furna and 800 ka for the Goian.

5.6.2.4 Imbrication

The imbrication of all deposits is more or less south, ranging from 130° to 210°. This means a flow direction out of the Rosal valley, down to the Miño. Imbrications north have not been found, so the route of the river which deposited the gravels is still uncertain. A map of the different imbrications is shown in figure 29.

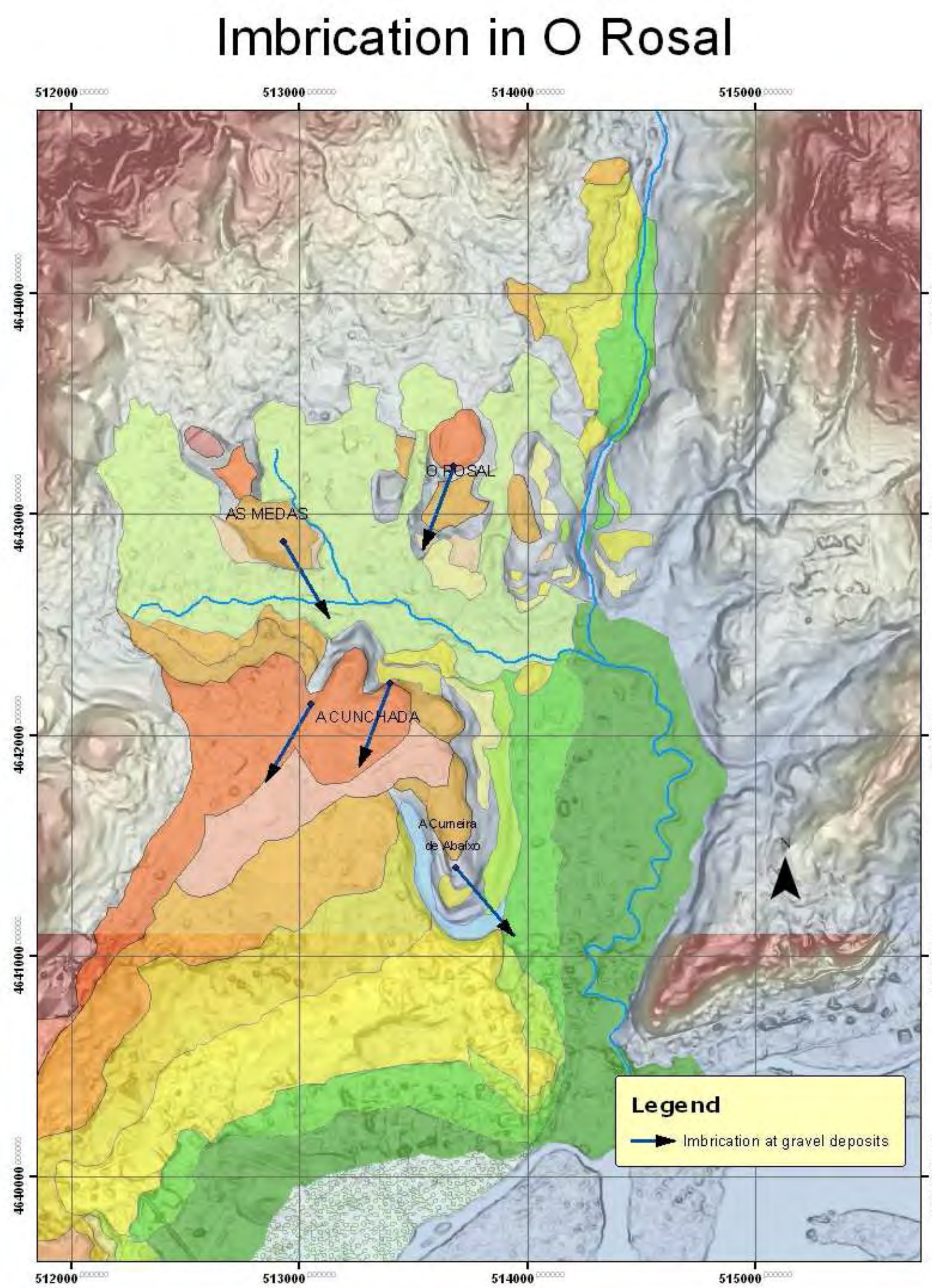

Figure 29: Imbrications at the different exposures in the O Rosal valley

5.6.2.5 Dipping deposits

In As Medas a deposit is found which dips 240° SW and in O Rosal a deposit which dips 345° NW.

Two of the exposures show a dipping deposit. These structures could display foresets which would imply they are deposited in a deltaic environment ("Foreset-bed" in Encyclopedia Brittanica Online, 2011; "Foreset-bed" in McGrawHill Science and Technology Encyclopedia, 2011; Spector, 2001; Stanley and Surdam, 1978). These encyclopaedias mention that the upper unit is sometimes less dipping than the lower part of the deposit, which is the case sometimes. Another possibility is that the gravel was deposited horizontally, but later has been tilted due to tectonic forces (Viveen, personal communication, 2010; Summerfield, 1991; Rainforth, 2004).
If the deposits show foresets, then the 50m terrace at O Rosal is deposited by a river coming from 165° SE, and the 40 m terrace at As Medas is deposited by a river coming from 60° NE. This is not found back in the imbrications. If the direction of 240° is continued on the map, one ends up west of San Dian, an area where gravel is not present anymore. Consequently it is unlikely the dipping of the deposit at As Medas shows foresets.

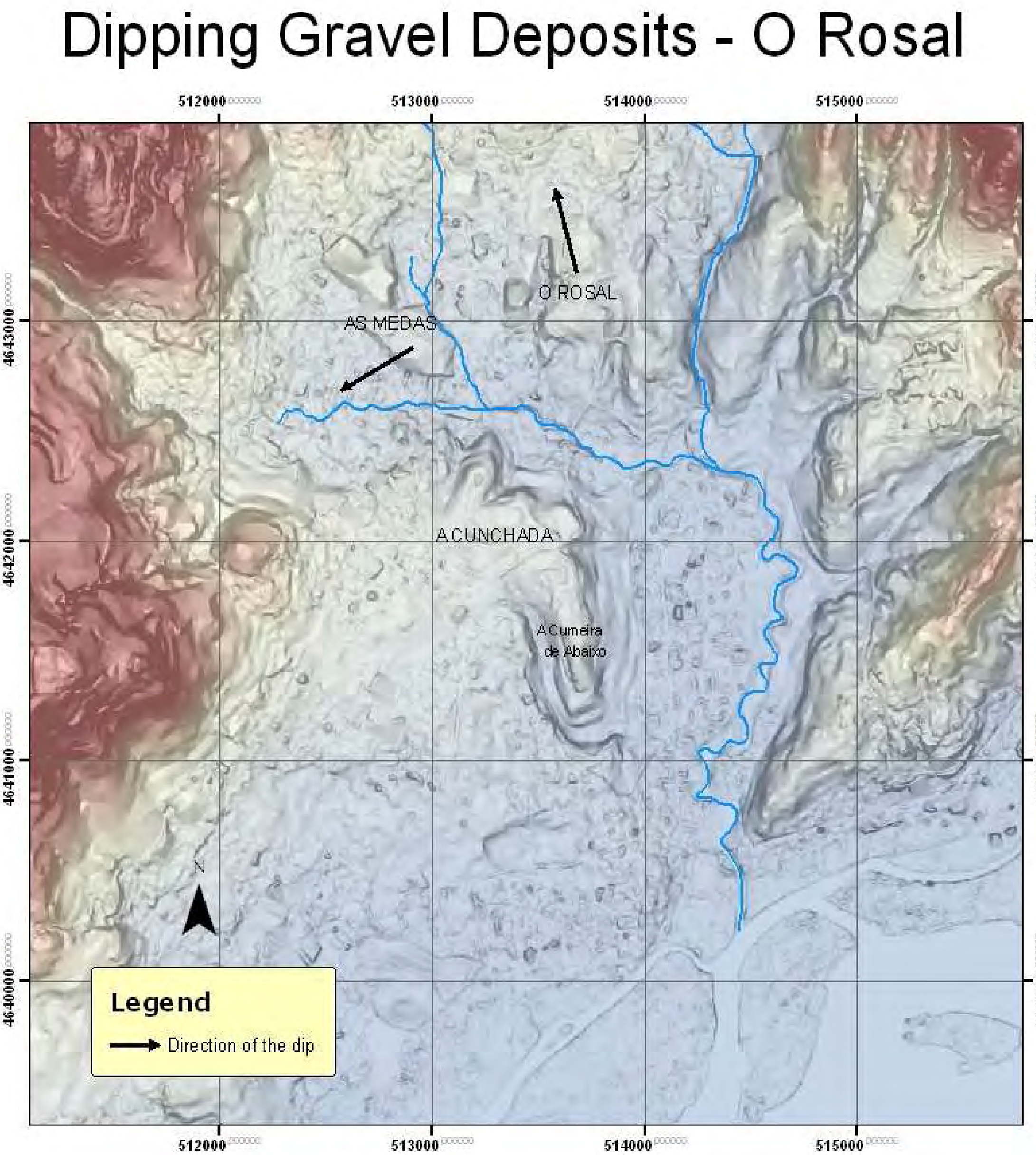

Figure 30: Dipping deposits in the O Rosal valley

If on the other hand tectonic tilt is responsible for the dipping of the gravel deposits, this means at least three different 'blocks' are present in the Rosal valley which have moved independently. The block of O Rosal tilting 345° NW, the block of As Medas tilting 240° SW and the block consisting of the exposures in PART I, where dipping structures are not found.
The Rosal valley shows some properties that show that tectonics are important in the area. At As Medas a broken quartz vein is found in sapprolite beneath the gravel deposit, which implies there has been pressure on the hardrock.

If the deposit at As Medas is tilted by only 10°, this means that the top and base of the deposit should be 17 meter higher, 100 meter to the 60° NE. This is not visible in the present topography, the hill is sloping up NE, but is eroded and excavated at many places. To the north sapprolite is found while the bottom of the deposits is not visible in the south, 9 meter lower. To the NE it is unclear if gravel is present due to construction.

At the hill of O Rosal, the altitude drops to 40 m. when travelling in the direction of the dip. Neither this is a very steep slope, but the lowering in topography makes the probability of tectonic tilt higher. It must be noted that erosion and deposition processes also have a large impact on the present topography (Summerfield, 1991).

5.6.3 Conclusion gravel deposits

From the weathering of the clasts in the exposures, and the analysis of terrace levels can be concluded that the deposits are probably very old. How old is not known, from several scenarios in section 5.5 showed that the minimum age of the deposit at the 20 m terrace possibly fluctuates between 175 and 400 ka, and for the deposit at the 40 m terrace between 400 and 860 ka. The gravel found at 40 m and 50 m probably belongs to the same one deposit, which is incised in two terrace levels. Exposures up to 7,2 m have been found, though it is not unthinkable that the total gravel column is higher.

All of the exposures show an imbrication to the south, south east, but it is unclear how the gravel entered the valley. On the dipping deposits at As Medas and O Rosal a dip towards the south west, respectively north-northwest is found. These dipping deposits probably show tectonic tilting, which means that blocks are moved apart from each other. In the next chapter these tectonics in the area will be discussed.

5.7 General Topography and Tectonics

First the general topography in the O Rosal valley is described, and then some possible solutions are given based on the information found in the deposits, and in literature.

5.7.1 General Topography

The O Rosal valley shows some interesting properties. It looks like a low lying 'bathtub' rather than a beautiful textbook V-shaped river valley. The Tamuxe flows on the extreme eastern side of the valley, and does not seem to have anything to do with the rest of the valley.
The big block of terraces consists of 7 terrace levels, all running more or less SW-NE, slightly half-moon shaped facing the Miño. In A Guarda the terraces merge with the large flat between mountains Sta. Tegra and Torroso. The terraces in the north of the O Rosal valley look like isolated islands in a further low lying landscape. Small creeks separate them from each other and from the block of terraces which lies to the Miño. Other creeks have incised behind the gravel deposits, making the hills even more isolated in the landscape.

From the isolated terraces in the upper O Rosal valley is believed that they have been incised by small creeks, to a 50 m and 40 m terrace. Because the 50 and 40 m terrace lie on both sides of the small creek. It is interesting that the small creeks have dissected the large deposits and made a very dominant terrace. As the Miño did not flow directly in the upper O Rosal valley anymore during the formation of the 40 m terrace, it is probable the small creeks incised this terrace.

The biggest creek which flows in the north of the O Rosal valley comes from the mountains and flow to the Tamuxe in more or less a straight line from the west to the east. All other creeks which run in the Rosal valley have an asymmetrical position, and rather lie on one side of the valley. The Tamuxe river lies totally in the east of the catchment; the small creek at As Medas runs south, then it meets the hill at As Medas, runs close to its border and merges with the creek flowing W-E. Above O Rosal a small creek starts flowing south towards the deposit, but then is diverged to the east instead, where it enters the Tamuxe upstream of the small gorge. The fourth creek in the valley flows from the south of A Cunchada first N-SE, until it abruptly changes its course 90 degrees (just north of 4641000) and starts flowing east towards the Tamuxe. This creek has incised 15-20 meter in the gravel deposits.

5.7.2 Tectonics in the O Rosal valley.

In the O Rosal valley differential tectonic tilt is probably of large importance. In this small chapter it is tried to visualise the different processes probably present in the valley.

5.7.2.1 Subsiding basin

First of all, the whole catchment is probably lowered. This can be advocated with the following arguments. The valley has a 'bathtub form', is very wide and flat going up very steeply at the edges. The Tamuxe river flows totally to the east, and enters from a small deep valley. The deposits lie at a location which is hard to reach for the river. Far away (5 km) from the present Miño river, in a valley flanked by high, straight and steep walls. In figure 31a the turn the Miño river must have made to deposit the gravels in the O Rosal valley, is shown. It seems illogical the river would enter the valley without 'external' forcing. The straight steep walls are an indication for possible faults (Summerfield, 1991). And other lowered basins are already described in the area. Butzer (1967) described the Louro valley as a lowered basin. Although clay deposits have not been found in the O Rosal valley, in both valleys thick deposits of extremely weathered quartzite are found (Butzer, 1967; Nonn, 1967). The two valleys have a similar form, with a low lying flat area surrounded on all sides by very steeply sloping flanks. In figure 31 the two valleys are shortly compared. The idea of uplifted and lowered blocks in the study area is also found by Butzer (1967), Trenhaile et al. (1997), Carvalho 1981 (In Granja, 1999).

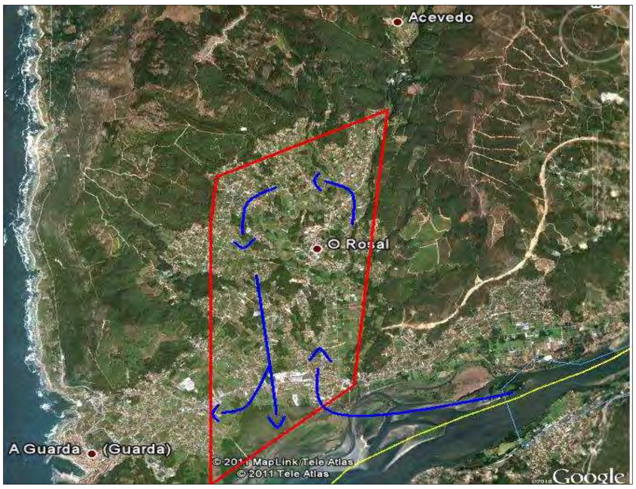

Figure 31 a,b: Short comparison of the valley form of the O Rosal valley (above) with the Louro valley (right). The red area is the area below 80m. Note the sharp turn the Miño has to make to enter the valley.
(Images from Google Earth, 2011)

The similarity of the deposits at As Medas and O Rosal suggests that it was originally one deposit, incised twice to form a 40 m and 50 m terrace, in one phase. This results in a gravel column of > 20 m. If the area was constantly subsiding, there would be more room deposition of gravels.

5.7.2.2 Tilt

The valley is probably tilting towards the east. On the eastern side of the Tamuxe river only a small T1a is found, while on the western side also a T1b, T2a and T2b are preserved, which implies the river is pushed towards the east and erodes its east bank more than its west. All creeks start flowing straight east as soon as they have the chance. It seems some rivers are first diverted towards a smaller tilting sub block, but than quickly change their course as they can.
Summerfield (1991) relates this to a graben system with different uplifted blocks. Which correspond with other ideas on tectonics in the area (Butzer, 1967). Blanco Chao et al. (2003) already mention the tilt around the coast, and with the N-S and E-W faults in the area (Blanco Chao et al., 2003; Blanco Chao et al., 2007; Nonn, 1967; Alonso and Pagés, 2007).

With the information obtained from the field and from the DEM a small map is made which is shown in figure 32. The different blocks are limited by the rivers which flow through the area, or where the rivers make a sharp turn. Active faults are recognised by straight abrupt changes in topography. In case of mountain slopes, this is accompanied by steep slopes with hardly any gullies. The method is less reliable when tectonics have been inactive for a while, as gullies formed in a tectonically quiet period might still be visible in the landscape (Summerfield, 1991). Although in the study area active and less active phases of tectonics have thought to have happened (Butzer, 1967), still, the straightness is used as an indication for a possible fault.

Apart from this some loose possible faults are drawn, based on a strong difference in topography. This is the case at the flanks of the catchment, changing from flat to steep slopes and in steep incised gullies east and west of O Rosal. Other possible faults are drawn near the creek flowing W-E, and at locations where a sudden transition from deep gravel deposits to sapprolite with no sediment at all is found.

Of course the map is based on numerous assumptions. A creek does not always run in a fault, and the sharp boundary of gravel depositions can also be found because it is simply the edge of the former river channel. The boundaries of the different blocks are a possibility, though there is not any proof for them. However, when looking at the map, it is found that most proposed faults run indeed along the agreed fault directions N-S and W-E (Blanco Chao et al., 2003; Blanco Chao et al., 2007; Nonn, 1967; Alonso and Pagés, 2007, Pliego Dones and Corretge (1978), Abril Hurtado and Corretge (1978)).

Probably the tilting in the O Rosal valley has been active, at least until recently. On one side of the valley still only a T1a is present while on the other side more levels are found. This implies that something probably pushed the river to the east and eroded away its own T1b, T2a, and T2b terrace. If the T1b has been formed during the last inter-glacial, we can conclude that the tilt towards the east has at least been active until then. The small creek running north of As Medas also seems to be drawn in the direction of the dip. The top of the hill at As Medas is indeed lower to the SW, and the top of the deposit at O Rosal is lower to the NNW. however the hills of As Medas and at O Rosal are still relatively flat on top. This suggests most tilting took place after the valley was filled with gravel, later fluvial events flattened the tops at 40 m, respectively 50 m after which tilt decreased and left the tops relatively flat.

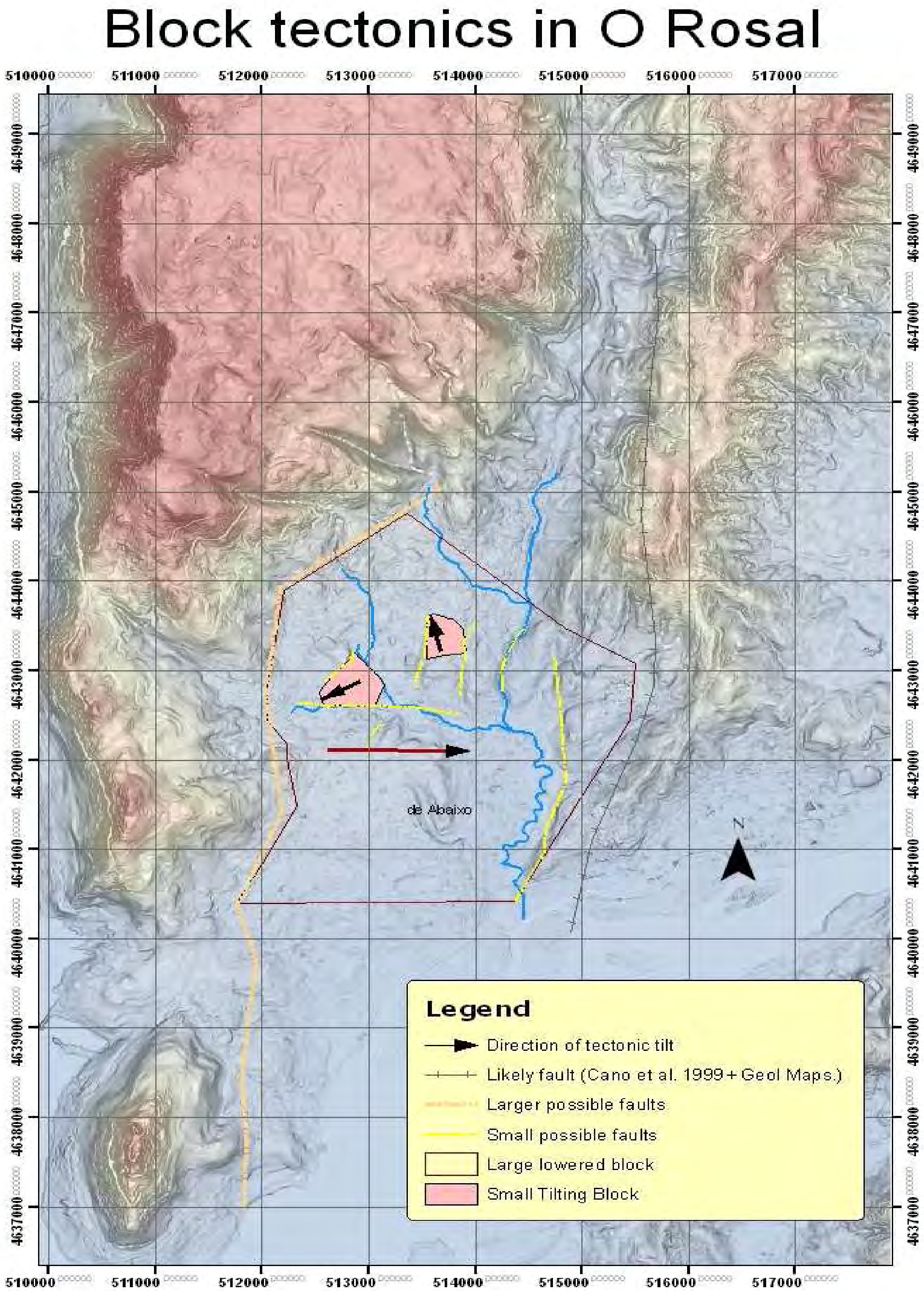

Figure 32: The found indications for possible tectonics in the area.

5.7.3 Conclusion

It is almost certain that the O Rosal valley is tilting towards the east. This is not just a part of the subsiding of the O Rosal valley, but happening along a large part of the Galician coast (Blanco-Chao et al., 2003). This is possibly an effect of the rift zone in front of Galicia (Sibuet et al, 1985; Pannekoek, 1966). At least two other blocks are tilting in the valley which are still believed to be active, though less than before. Apart from the tectonically tilted blocks, also a few possible faults have been recognised, based on straight boundaries in the topography (Burbank and Anderson, 2001; Summerfield, 1991). The direction of possible faults in the area corresponds with the direction other authors have given for the faults in Galicia, range either N-S of E-W.

The created map in combination with the strong boundaries in topography in the valley give a good indication for the possibility of faults and tectonics, and is a good start for further research.

6. Discussion

Most of the results have already been discussed in the chapters before, so I will shortly summarise the discussion of the different chapters here to form this overall discussion.

Terrace identification

The terraces have been identified as relatively flat stretches with terrace scarps, possibly by doing this also terrace levels covered with colluvia; or man-made terraces have been accidently identified as terrace. In order to make the interpretation more reliable, I have looked for gravels to prove fluvial or marine origin.
Most of the terraces which are found in the area correspond well with what other authors found, though often a different identification of the altitude has been made. As discussed in section 5.5.3, this is possibly due to differences in the source of altitude used, as different maps not always agree on the height of a certain place.
The height intervals used in this research are smaller than the intervals used by many other authors (Teixeira, 1952; Butzer, 1967; Cano Pan et al., 1997). Personally I think this is necessary, because otherwise different terraces can fall in the same range, and the height identification becomes meaningless. The step between two terraces is sometimes only 2 m. On the other hand, with very small ranges slight coincidental differences in altitude have a large impact on the analysis of the terrace sequences which is a problem in an area partly covered by colluvium (Alonso and Pages; 2007; Blanco Chao et al., 2003; Butzer, 1967; Texier and Meireles, 2000). In order to overcome this problem, the levels with the largest surface, most occurrences and presence of gravel have been selected as they are thought to be most reliable.

The most reliable terraces have been compared with the terraces of the other parts of the study area and from this the corresponding terraces are filtered. This gave quite good results with 9 corresponding levels up to 60 m. From this we can conclude that the terrace levels probably formed around during the same time, and differential uplifting has probably been absent in the area since the formation of the 60 m terrace.

Terrace formation

The most important process behind the formation of the marine and fluvial terrace levels is believed to be sea level fluctuation and climate change. Marine terraces are formed during a period of stable sea level (Hearty et al., 2007), and fluvial terraces are formed when a river incises in its own sediment, possibly by base level drop. In the study area the sea level is the base level. The periods during which the marine and fluvial terraces are formed are probably inter-glacial periods with sea level high-stands. During sea level high stands the sea level is stable over a longer period of time, which gives the sea the possibility to form marine terraces (James et al., 1971). At the beginning and end of the inter-glacial high-stands fluvial deposits are probably laid down due to higher discharges and sediment loads (Stemerink et al, 2010; Tebbens et al., 2000), while at the turn from inter-glacial to glacial periods also an increase in gradient, due to base level drop, favoured caused an energetic environment in which gravels could be transported and deposited in the lower Miño. As sea level lowered further, the deposits were incised, leaving terraces in the landscape. If the terraces would be formed during sea level low-stands, the uplift in the area needs to be very high. Since very little information on uplift rates in the study area is found, this is not thought to be the case.
The terraces up to 60 m are believed to have been formed in the Quaternary, while sea level did not reach a level higher than + 20 m in this period (Bintanja et al., 2005; Bintanja and van de Wal, 2008 in de Boer et al., 2010; Lisiecki and Raymo, 2005). Therefore it is proposed the area is uplifting.

Process behind sea level fluctuation

The Milankovitch cycles are thought to be the key process behind the sea level; fluctuations, since changes in solar influx strongly influence the water stored as ice and consequently the sea level (Miall, 1997). The dominant 100-ky cycle over the last ± 800 ka (Miller et al., 2005), has probably had the most effect on terrace formation. The 100-ky cycle possibly has a more pronounced influence on water stored in ice and consequently sea level than the 41 ky-cycle which is prominent before 1100 ka.

Terrace level - Sea level analysis

Several terrace – sea level correlation scenarios have been analysed, with constant and variable uplift rates. As little information is known in the area the lowest level is proposed to be Eemian, and the rest of the terrace levels formed during earlier high-stands. The exact correlation is unsure, because none of the scenarios is truly convincing. Due to the strong difference in sea level during sea level high stands, scenarios with constant uplift rates have a very poor correlation and, it is believed that periods of uplift have been alternated with short periods of subsidence. Because information on the uplift rate is not known a conservative scenario with low uplift and subsidence rates, and smooth transitions between the two, is believed to be the most convincing. This scenario places the terrace formation between the Eemian inter-glacial and 1100 ka.

Topography O Rosal valley

In the O Rosal valley structures have been found in exposures of gravel deposits. Analysis of these structures, and analysis of the general topography of the valley, leads to the idea that tectonic tilt and subsidence are important processes in the area. The structures in gravel deposits, asymmetrical position of the creeks and the sharp, straight boundaries in topography have been interpreted as indication for tectonic activity with the use of literature on the subject (Summerfield, 1991; Burbank and Anderson, 2001). Some possible faults have been drawn on locations where the topography showed properties, which were similar to fault properties described in literature. It must be noted that the faults and the boundaries are an indication. Although the subsiding basin and the tilting blocks are almost certainly present, more research is needed to draw them all up.

The 40 m terrace in the upper O Rosal valley lies in between 50 m terraces, which can be explained in several ways. One explanation could be that the terrace has been lowered 10 m, as a terrace on sapprolite on 50 m is found next to it, and the deposit shows possible tectonic tilt, which indicates tectonic movement. On the other hand it is very coincidental that the block would have been lowered exactly 10 m. Therefore it is proposed that the deposit was laid down up to 50 m and was later incised to a 40 m terrace by a creek flowing in the upper Rosal valley. This hypothesis is founded by the occurrence of another 40 m terrace on the opposite side of the valley at A Cunchada. A problem with this hypothesis is that not a lot of creeks flow through upper O Rosal valley, and the catchment of these creeks is very small. Possibly the Miño sometimes entered the upper Rosal valley via the Tamuxe and its side creek and helped with the removal of the sediment.

7. Conclusion

This research on the Miño estuary analyses the marine and fluvial terraces along the coast and in the O Rosal valley in southern Galicia, and processes possible responsible for their formation.

Terraces

The terrace maps made are of higher spatial resolution than the terrace maps already made by other authors (Cano Pan et al., 1997; Hurtado and Corretge, 1978; Dones et al., 1978; Dones and Corretge, 1978) and are therefore thought to give a more complete overview of the terraces along the Atlantic coast and in the O Rosal valley.

Terraces have been found up to 105 m along the coast, and up to 60 m in the O Rosal valley. Along the Portuguese coast more and bigger terrace levels have been preserved than along the Spanish coast. This is possibly caused by less steep slopes along the Portuguese coast, which favoured terrace preservation. Along the Spanish and Portuguese coast most terraces are preserved in locations which are more sheltered to wave erosion, like small inlets in the coast.

The highest convincing terrace is the 60 meter terrace, at the same height as an old Miño passage at A Guarda, earlier described by Butzer (1967). The hypothesis of the old river passage is confirmed by the occurrence of other 60 m terraces in the O Rosal valley and along the Portuguese coast, and by the shape of the younger Miño terraces pointing in the direction of the 60 m terrace.

From a comparison of the marine terraces with the fluvial terraces, follows that reliable corresponding terraces are found at 7 m, 15 m, 20 m, 26 m, 29,5 m, 35 m, 40 m, 50 m and 60 m. From the good correspondence between the terrace levels in the three parts of the study area is concluded that differential uplift probably did not take place since the formation of the 60 m terrace.

Terrace formation

It is believed the corresponding marine and fluvial terrace levels were formed respectively during, and around sea level high-stands. These high-stands in turn are caused by the Milankovitch cycles.

It is believed the marine and fluvial terraces which correspond in altitude are formed around the same sea level high stands. The marine terraces were formed by constant erosion in a period of high stable sea level during inter-glacial periods. Fluvial deposits were laid down in transition periods to and from inter-glacial circumstances. The deposition is believed to be caused by an increase in discharge and sediment supply, related to a change in climate at the beginning of the inter-glacial periods. As sea level lowering continued, the deposits were incised and left in the landscape.

The 4 meter terrace and the 45 meter terrace in the O Rosal valley do not have a correlating marine equivalent. Which implies that they have probably not been formed at sea level. It is proposed they have been deposited due to an increase in sediment during the change from inter-glacial to glacial circumstances. After the formation of the 7 and 50 m terrace, base level drop and climate change caused the river to carry more and larger sediment. This was deposited just below the incised terrace level and incised when sea level continued to drop.

Terrace level - Sea level analysis

From the comparison of the different terrace heights with former sea level was concluded that the area has been uplifted in the past. Analyzing different scenarios has lead to the conclusion that the uplift rate in the study area was probably variable and periods with uplift have been alternated by periods with subsidence. A scenario with conservative uplift and subsidence rates seems at the moment the most convincing. In this scenario the 7 m terrace is formed during MIS 5e; 15 m terrace during MIS 9; 20 m terrace during MIS 11; 26 m terrace during MIS 15; 29,5 m terrace during MIS 17; 35 m terrace during MIS 19; 40 m terrace during MIS 21; 50 m terrace during MIS 25; and the 60 m terrace during MIS 27, a little over 1 Ma in age. This corresponds with a varying uplift rate between 0,032 mm/y (690 - 778 ka) and 0,13 mm/y (403 – 575 ka); between 778 and 860 ka the subsidence was -0,089 mm/y.

Other flat terrace levels along the coast are either overlain by colluvia, or man-made terraces.

Sediments

Along the coast undisturbed, in-situ ancient beaches were not encountered, but the O Rosal valley contains many thick gravel deposits, incised by small creeks. Based on the composition of the gravel deposits is concluded that these have been formed by the Miño.

Tectonics

It is believed the O Rosal valley has been lowered tectonically, and that the whole O Rosal valley is tilting towards the east, while sub blocks within this valley are tilting towards the NNW or SW. The edges of the tilting blocks and possible faults have been drawn based on some differences in topography, however it must be noted that there is not any proof for these faults. The possible faults that are proposed all lie N-S, E-W or NE-SW which is in correspondence with the general direction of the faults in the area (Blanco Chao et al., 2003; Blanco Chao et al., 2007; Nonn, 1967; Alonso and Pagés, 2007; Pliego Dones and Corretge, 1978; Abril Hurtado and Corretge, 1978).

The 40 m terrace in the upper Rosal valley lies in between 50 m terraces. Which means that this terrace is probably incised by small creeks flowing through the gravel deposit.

So to answer my research questions as mentioned in chapter 3:

Where can terraces be found and how are they composed?

Terrace sequences can be found in the O Rosal valley, along the Spanish coast and along the Portuguese coast. Along the Spanish coast T1 (5-10 m), T2 (11-15 m), T3 (18-22 m), T4a (28-33m), T4b (33-38 m), T5 (39-43 m) T6 (47-50 m) and T7 (57-62 m) are present; Along the Portuguese coast T1 (5-10 m), T2 (14-17 m), T3a (20-25 m), T3b (25-28 m), T4a (28-33 m), T5 (38-41 m), T6 (48-52 m) and T7 (58-62 m); and in the O Rosal valley convincing terraces are at T1a (4-7 m), T1b (8-10 m), T2b (15-17 m), T3b (25-27 m), T4b (35-36 m), T5a (39-43 m), T5b (45-48 m), T6a (49-51 m), T7 (59-61 m). Along the coast the levels are especially well persevered in small depressions which shelter the terraces from the sea. In Oia and A Guarda the largest
The marine terraces are overlain on soils with unknown depth, with very fresh, well rounded quartzite, granite and gneiss gravels on T1 and T2, and occasional quartzite gravels up to T6a (50 m).

The terraces rise from sea level to the north of the valley up to a height of 50m, they face the Miño in the shape of a half moon. In A Guarda a terrace level is found which connects the marine terraces with the fluvial terraces at 60m. Along the Tamuxe, also terraces are found, these however are formed by the Tamuxe, and not taken further into account

Is there a link between the fluvial and marine terraces of the Miño?

Yes, the levels at 7m, 15m, 20m, 26m, 29,5m, 35m, 40m, 50, and 60m occur on all fronts. This implies that they have been formed during the same time, around inter-glacial periods.

How are these terraces probably formed?

The marine terraces have been formed by marine abrasion during inter-glacials. The fluvial terraces are formed by deposition during a change from glacial to inter-glacial, or inter-glacial to glacial under chaotic climatic and energetic fluvial circumstances with a lot of runoff, while also an increase in gradient due to a lower sea level might have favoured the transport of larger particles. The river flattened the deposits when the river still flowed more or less at sea level highstand, and the terraces were formed during subsequent incision caused by sea level drop. As uplift is present in the area, next sea level high-stands did not reach the deposits anymore.

Which other processes are important in the study area?

Tectonics are very important in the area as several deposits in the O Rosal valley are tilting. The whole valley is tilting towards the east and two deposits show a tectonic tilt to the NNW, respectively the SW. The O Rosal valley is probably subsided, which explains the large flat area in between steep mountains, and the large depth of the gravel deposits.

Along the coast colluvial deposits are important; they probably cover many terrace levels.

8. Recommendations for future research

In this research several questions were encountered which are interesting to solve, and might aid future research on the area.

My research correlates terraces in the three parts of the study area. It is however not known, if these terraces are actually formed in the same period, or if they have moved relative to one another. Therefore It would be very interesting to date terraces. This would check whether the correlation I made is correct, and form these data a reliable uplift rate for the area could be calculated. At the moment Viveen et al. are working on this.

An interesting question is how the flow of the Miño went through the O Rosal valley, as in the deposits only imbrications to the south were found, though no imbrications entering the valley.

Another interesting question which raises this research is the origin of the structures in gravel deposits, and topographic features encountered in the O Rosal valley. They are believed to be formed by tectonics, though unfortunately it was not in the scope of this research to pay more attention to them. It would be very interesting to connect these small scale tectonics to larger tectonic structures to get an idea how the landscape is changing.

It is interesting to see that several Rias have been formed along estuaries in the Galiacian coast, but not at the Miño. It would be interesting to find out what the cause is for this difference.

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