QUATERNARY TO RECENT DRAINAGE EVOLUTION OF THE RAMBLA DE LUCAINENA, SE SPAIN

JOANNE LOUISE ROSSO

A thesis submitted in partial fulfilment of the requirements of the University of Greenwich for the Degree of Master of Philosophy

October 1997

ABSTRACT

The study is focused on the small drainage catchment of the Rambla de Lucainena, situated between the Carboneras and Sorbas basins of the Almeria Province in SE Spain. Previous research has shown that this river has developed due to aggressive headcutting during the Plio/Pleistocene, which has been strongly influenced by the unique climate and active tectonics of this semi-arid area. Fluvial incision during the Quaternary has left a series of terrace fragments from which four important terrace groups have been identified.

This study has taken a unique approach by integrating the analysis of contemporary process data and incorporating it into the interpretations of the Quaternary landforms. This approach has emphasised the differences between fluvial processes in semi-arid areas and temperate regions, a factor which is frequently ignored in reconstructing drainage within semi-arid fluvial studies. This is one of the first studies of drainage reconstruction to adopt this approach and it is hoped that it will highlight the need for the integration of contemporary and past data to develop a fuller understanding of fluvial history.

Of the four terrace levels identified here, two are of particular palaeoenvironmental importance. The oldest of these episodes is documented by the presence of fractured clast pairs within one of these terrace levels, interpreted as the product of frost weathering. This implies a period of periglacial conditions during the Quaternary. The second event of significance is recorded by a 20 m thick deposit of aggradational fines which indicates a period of increased precipitation and a much wetter climate regime. These observations conflict with the simple view of Quaternary palaeoclimate, that of increasing aridity during glacial periods which is widely followed in the Quaternary literature on SE Spain. The observations here suggest, as one might expect, that the palaeoclimatic record is more complex and requires further investigation. Of particular importance is establishing some form of dating control for these events, the absence of which generally limits the wider significance of the observations reported here. This work, however, demonstrates for the first time the palaeoclimatic significance of the Quaternary sediments and landforms of SE Spain, an aspect which has frequently been neglected, since they are commonly used to interpret the tectonic evolution of the area.

ACKNOWLEDGEMENTS

First and foremost I would like to thank my supervisors Dr Matthew Bennett and Dr Peter Doyle for their continuing support, help and enthusiasm during this project and the preparation of this thesis. I would particularly like to thank Matthew for his patience and humour throughout numerous editing sessions and Pete for his support in the field and his excellent digging skills. I would also like to thank Dr Anne Mather for her collaboration on the project, especially for the concept of the original project and for her guidance during the early field days.

The School of Earth and Environmental Sciences, particularly Professor Alistair Baxter and Dr Andy Bussell, deserve special thanks for their financial support during the field seasons associated with this project, without which the undertaking of this project would have been impossible.

A special note of thanks goes to my husband Stuart Rosso who willingly gave up his holidays to be my field assistant and also put up with the emotional highs and lows of an often neurotic wife. A further note of thanks needs to go to Dr Alistair Wells who provided invaluable assistance in the field, as well as being an excellent wall to bounce ideas off and a computer genius.

I would particularly like to thank Laura Walkingshaw for her help and friendship during the production of this project, especially for putting up with numerous discussions and reading many drafts. My thanks also go to Kate Spencer and John Howitt who provided many lucrative discussions and chats which were welcome distractions from work.

This work has also benefited from discussion with Dr Dave Horne, Dr Dave Wray, Dr Ian Platten, Dr Gareth George and Fiona Cocks, all of whom I thank for their expertise and for giving up their time.

I would also like to thank Lyndi Walsh of the Cortijo Urra field centre for her hospitality and Medway Campus library for their help with finding often obscure references. I am also grateful for the technical support of Dr Florence Lowry, Hilary Foxwell, Pat Brown and John Maddicks.

Lastly, my thanks go to my parents for their constant encouragement and words of advice and wisdom, as well as for their financial support over the years.

CONTENTS

LIST OF TABLES *Page No.*

LIST OF FIGURES *Page No.*

Chapter 1.0

1.0 INTRODUCTION

The aim of this research is to unravel the drainage history of the Rambla de Lucainena from the landforms and sediments within its catchment and identify both the intrinsic and extrinsic factors which have controlled this drainage evolution. In doing this the potential of palaeoenvironmental information concerning Quaternary environmental change in SE Spain will also be revealed. The Rambla de Lucainena is a small river located in the Almeria Province of SE Spain. It has increased its drainage area through aggressive headcutting and river capture during the pre- to early Quaternary and provides an ideal case history of the role of climate change and tectonic activity on drainage evolution in semi-arid regions.

The rationale for this work is fourfold. First on a global scale it adds to our understanding of the response of rivers to changes in climatic and tectonic regime, which although widely described in the literature (e.g. Gregory, 1976; Baker, 1977; Park, 1981; Collinson & Lewin, 1983; Nolan & Marron, 1985; Huckleberry, 1994a; Huckleberry, 1994b; Rumsby & Macklin, 1994), is still relatively poorly understood. This reflects in part the importance of site specific factors in determining fluvial response (Schumm, 1972) and highlights the need for the provision of site specific case studies such as this one. Secondly on a regional scale this work is of importance since drainage evolution through aggressive headcutting and river capture is characteristic of many rivers in SE Spain (Mather & Harvey, 1995). Thirdly, to demonstrate the potential of this type of evidence in making palaeoclimatic inferences about this region during the Quaternary, something which has been poorly explored in SE Spain to date. Finally at a local scale this work helps complete the Quaternary drainage history of the Sorbas region (Mather & Harvey, 1995).

In the remainder of this chapter the study area is first introduced and previous work within this region reviewed, before the problems of drainage reconstruction are discussed.

1.1 THE STUDY AREA

1.1.1 Geographical setting

The study concentrates on the small drainage basin of the Rambla de Lucainena which is approximately 90 km^2 in area. It is situated within the Almeria Province of SE Spain and extends between the Sorbas and Carboneras basins (Fig. 1.1). The Sorbas and Carboneras basins are east-west orientated Neogene basins divided by the basement rocks of the Sierra de Alhamilla.

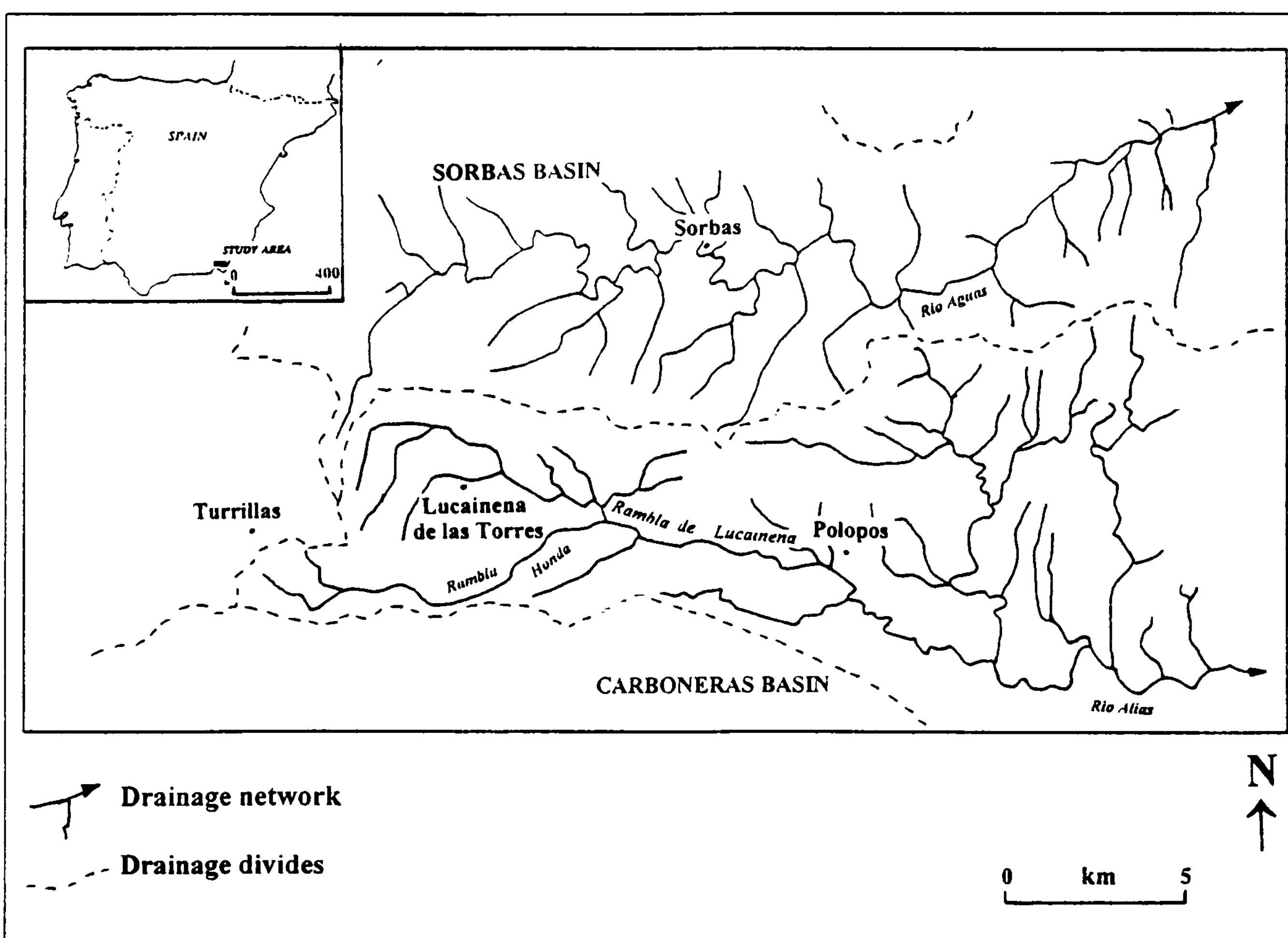


Fig. 1.1 Location of study area

The Rambla de Lucainena flows eastwards with the catchment beginning just to the north-west of Lucainena de las Torres (682 996- Tabernas Sheet 1030) draining into the Rio Alias at its eastern end (864 948- Sorbas Sheet 1031) and provides substantial drainage for the areas to the south of Sorbas between Tabernas and Carboneras. The river runs from a high of 600m above sea-level in the west to a low of 200m in the south east. The stream order calculated by the Shreve method (Section 2.2.1) is 44 and the density of the drainage network is 1.08 km per km^2. The overall drainage pattern is dendritic.

Two small villages are found within the Lucainena drainage basin, its namesake, Lucainena de Las Torres, on the south side of the river in the west and Polopos on the north side of the river in the east. The population of both of these villages is less than 300 people. A road runs between Lucainena de Las Torres and Polopos which at one point runs along the river bed of the present day Rambla de Lucainena.

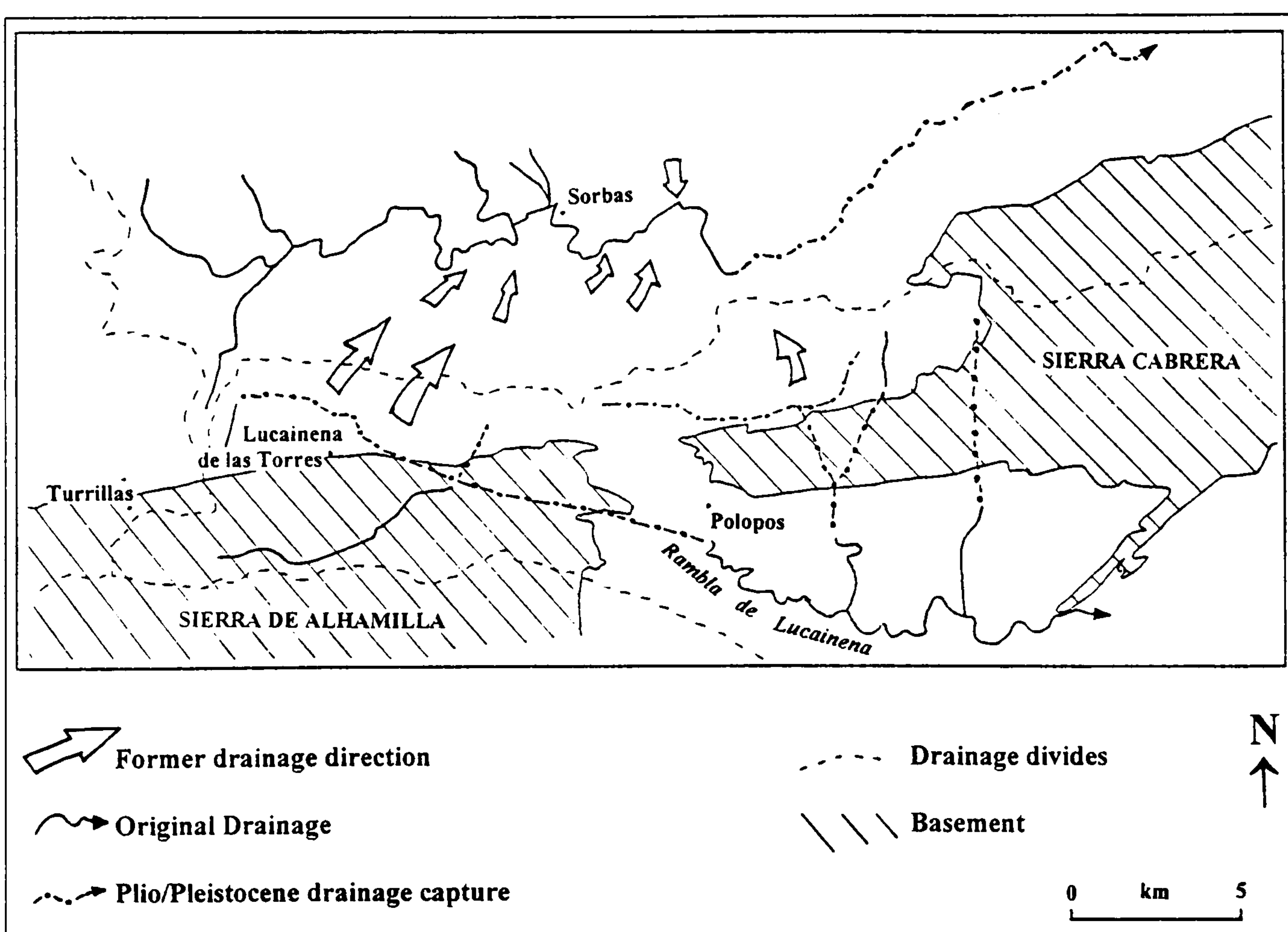


Fig. 1.2 Drainage evolution of the Rambla de Lucainena
Adapted from: Harvey & Wells, 1987

The Rambla de Lucainena is a complex drainage system which like many rivers in SE Spain has evolved due to the unique topography, climate and tectonics of the region (Mather & Harvey, 1995). The Rambla cuts through a range of lithologies and topographies, and crosses the strike-slip and reverse faults of the Northern Boundary Fault and also the Sierra de Alhamilla which is a major axis of uplift (Fig. 1.5).

This Rambla was initiated in the early Pliocene and has evolved by aggressive headcutting and westward incision which was the result of base-level change due to the withdrawal of the last Pliocene marine incursion (Mather, 1993a; Mather & Harvey, 1995; Fig 1.2).

1.1.2 Geological setting

The geological setting of the region has been extensively studied and good summaries can be found within the literature (e.g. Weijermars, 1985; Martin & Braga, 1994). The stratigraphy of the area is complex and varies from basin to basin, and only a brief summary is provided here. Terminology at Formation level has only been included where it aids the understanding of the geology within the Lucainena catchment.

Geology of the study area

The Almeria region lies to the eastern corner of the Beitic Cordillera. This mountain system consists mainly of Palaeozoic to Triassic metamorphosed rocks and formed due to collision between the European and African plates, during Jurassic to Miocene times (Smith & Woodcock, 1982; Harvey, 1987; Harvey & Wells, 1987). These mountain ranges are separated by a series of more recently formed Neogene sedimentary basins in which thick sequences of sediments have built up (Fig. 1.2). The basin sediments mainly consist of upper Miocene marine clastic sediments which lie unconformably over the basement rocks (Harvey & Wells, 1987). Figure 1.3 summarises the stratigraphy of the Sorbas Basin, which is similar to the stratigraphy of the study area, although local variations occur which are indicated in the text below.

The lowest part of the upper Miocene sequence consists of the Tortonian sediments which are steeply dipping and folded in an east-west direction. These sediments are thick turbidite sequences consisting of conglomerates, sandstones and marls (Haughton, 1994).

The Tortonian strata is unconformably overlain by Messinian evaporite rocks which are characterised by the thick gypsum deposits of the Yesares Formation (Van de Poel, 1991) which due to the salinity crisis covered the whole of the western Mediterranean (Hsu *et al.*, 1977; Weijermars *et al.*, 1985). The lower part of the sequence is transgressive, forming an onlap surface over the marine and coastal sediments (Dronkert, 1976; Weijermars *et al.*, 1985). The nature of these sediments varies from basin to basin but at the base generally consists of Azagador limestone containing both basal conglomerates and mixed brown to yellow, siliciclastic and bioclastic sandstones (Van de Poel, 1991). Following this unit is the Abad Marl which grades from a light greenish colour in the lower unit to a darker yellowish colour in the Upper and is capped by a white powdery diatomite surface. Above this lies the Cantera Reef limestone which was seen to prograde over the Abad Marl in the area around Polopos (Mather, 1993a).

During the latest Messinian and Pliocene marine conditions returned (Addicott *et al.*, 1978) and limestones were deposited (Martin & Braga, 1994). During the Plio/Pleistocene epoch sediments were deposited across the region, each consisting of a very localised stratigraphy. Therefore, these formations have been given different names for different localities. Where it is found in the Sorbas basin it is termed the Gochar formation (Mather, 1993a, Mather & Harvey, 1995) and where it is found in the Carboneras basin it is called the Polopos Formation (Mather, 1993b). The latter is due to its locality being close to the town of Polopos, and is the most important to this study because the Rambla de Lucainena runs through it. The Formation has been studied by workers such as Mather (1993b) and Mather & Westhead (1993) and has been found to form an erosive base overlain predominately by well-bedded cobble and boulder conglomerates.

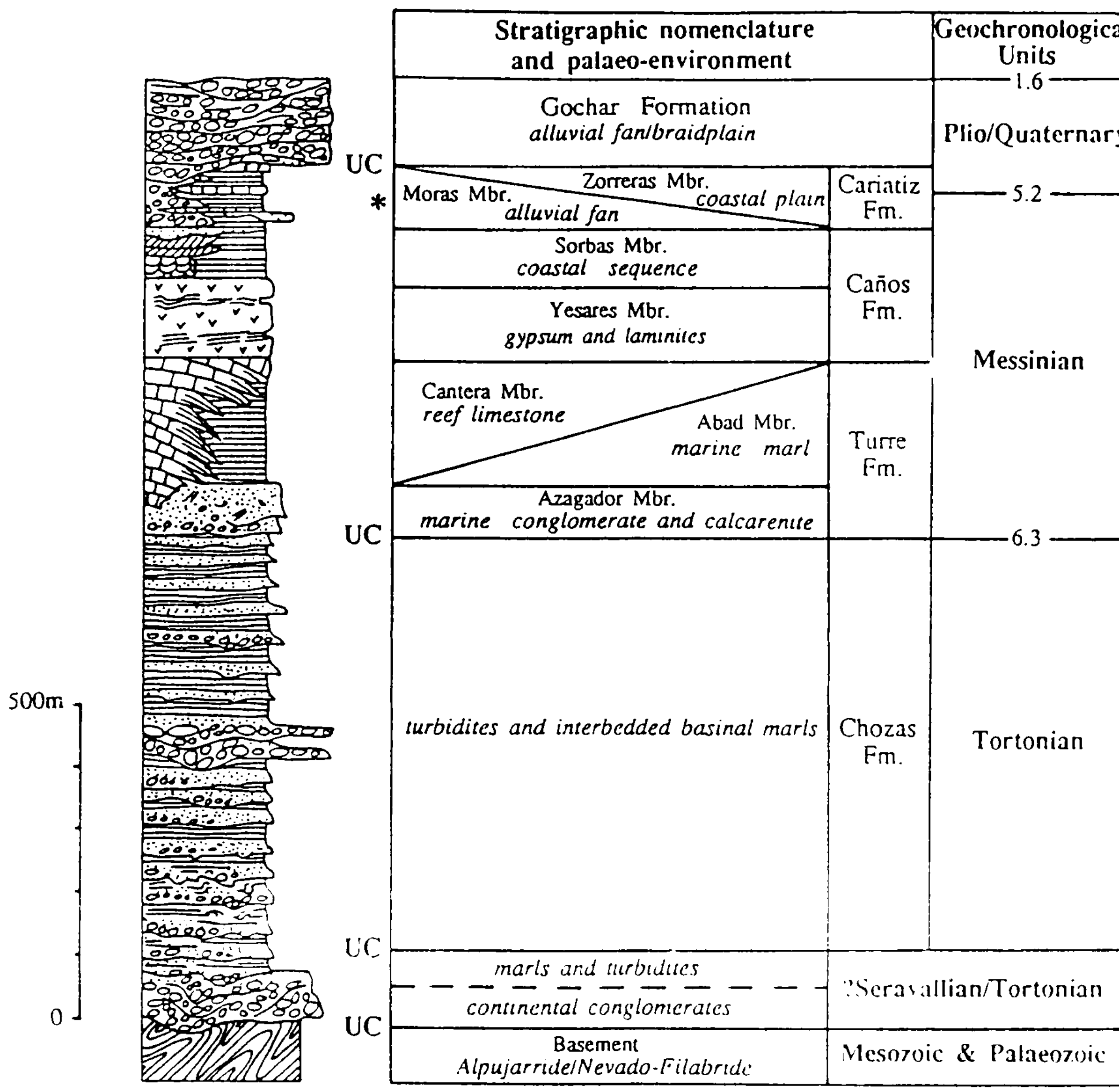


Fig. 1.3 Neogene stratigraphy of the Sorbas Basin.
Taken from: Mather & Harvey, 1995. Note age divisions are mainly relative and U.C. indicates the principal unconformities.

Tectonic setting of study area

In the latest part of the Neogene, the Pliocene epoch, it has been suggested by Rios (1978) and Postma (1984) that the Beitic Cordillera underwent epierogenic uplift and deformation (Harvey & Wells, 1987) which was followed by continued tectonic activity during the Quaternary (Dumas *et al.*, 1978). Uplift in the late Pliocene elevated a limestone bed estimated to be early Messinian in age (Roep *et al.*, 1979; Weijermars *et al.*, 1985). This formed a platform to the south and a regional slope on which drainage was established (Harvey & Wells, 1987).

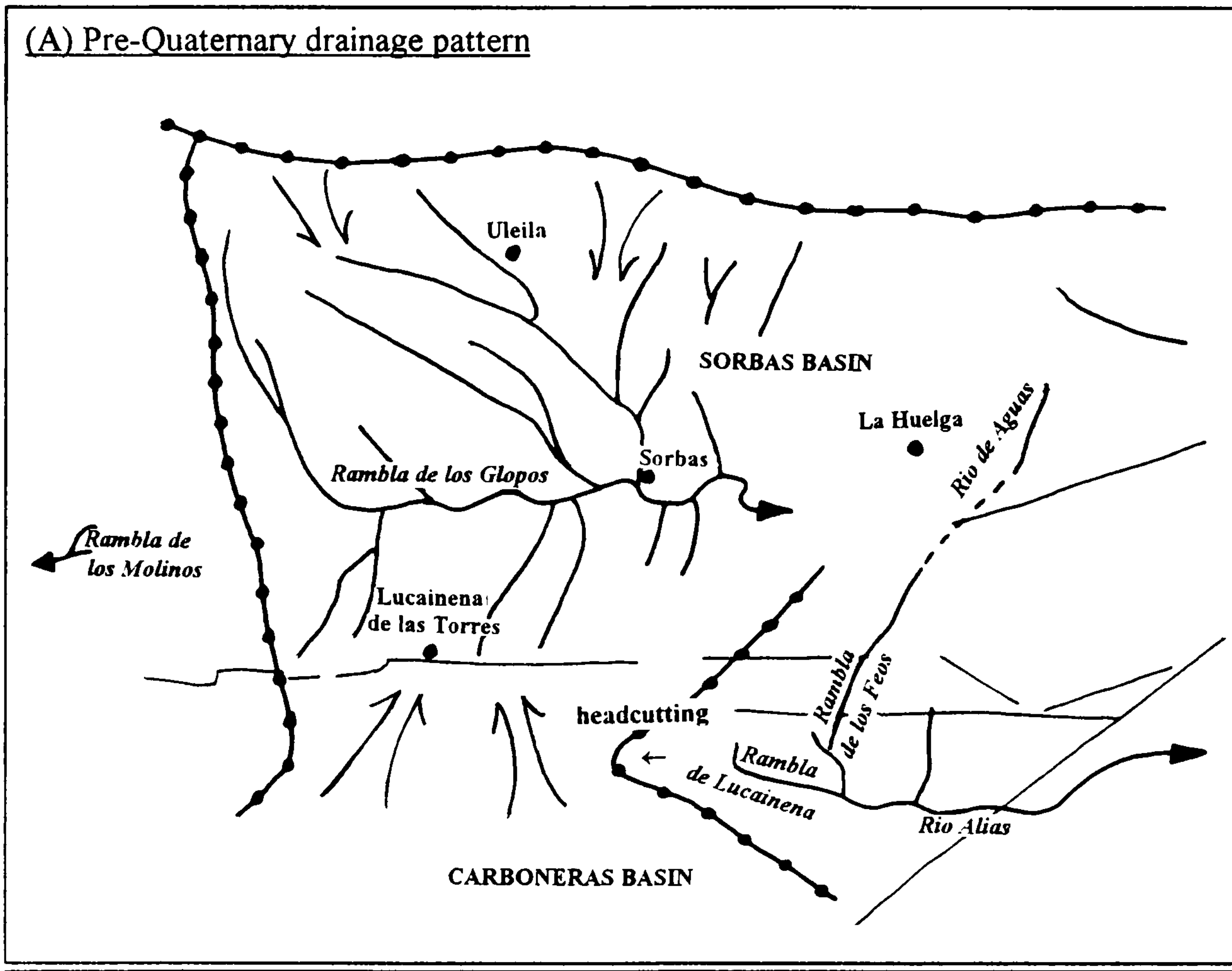
Geologic and tectonic factors together with the increased erosion rates associated with semi-arid environments have led to the unique morphology and drainage evolution of the Beitic Cordillera. The rocks, morphology and consequently the drainage of the area have also been affected by more recent Pliocene and Quaternary tectonism.

1.1.3 Geomorphological Setting

The regional geomorphology of SE Spain can be identified by the mountains of the Sierras and the plains of the basin fill. The geology and tectonics of the region have had a dominant role in shaping this landscape. On a smaller scale the climate, surface and fluvial processes have been fundamental in shaping the detail of the Lucainena basin from the Quaternary through to the present.

Quaternary Drainage

The drainage pattern of the Rambla de Lucainena has developed due to both active and passive tectonics following the withdrawal of the last Pliocene marine incursion. Passive tectonics were influential in providing lines of weakness along favourable structures, encouraging aggressive headward cutting river systems, such as the Rambla de Lucainena (Mather & Harvey, 1995). The original Lucainena drainage pattern in the late Pliocene was small. It drained west to east into the Rio Alias (Fig. 1.4A). The predominant feeder into the Alias at that time was the Rambla de los Feos, which according to Harvey and Wells (1987) also drained the upper Aguas system through a topographic low. Aggressive river development incised into and headcut across the basement schists of the Sierra de Alhamilla and then cut through the steeply dipping Tortonian strata (Fig. 1.4B). The Rambla developed parallel to the strike of the lithologically weaker Tortonian strata and successively captured former south to north flowing drainage of the Sorbas basin (Mather, 1993a; Mather & Harvey, 1995; Fig. 1.4C).



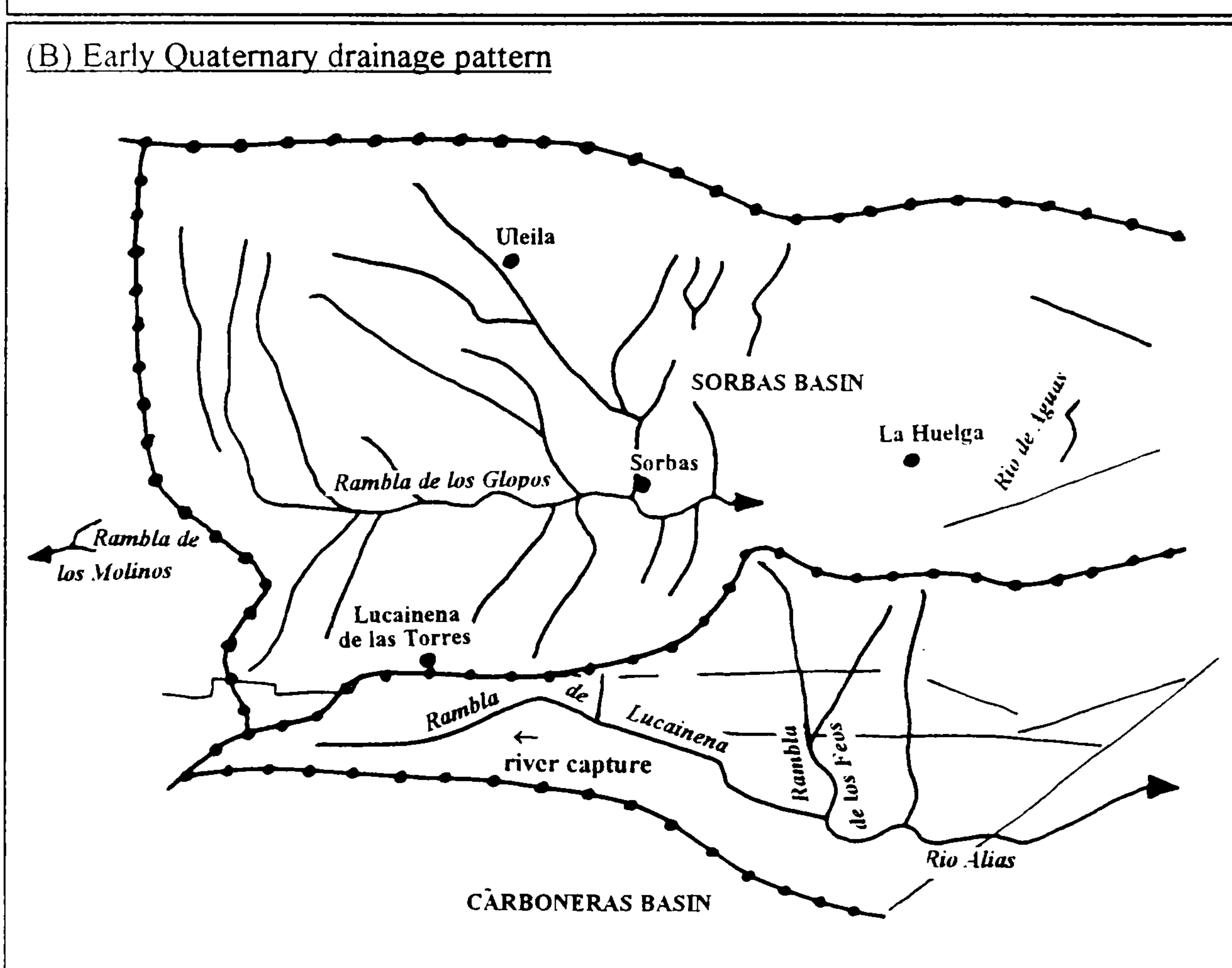


Fig. 1.4 (see over for explanation)

(C) Current drainage pattern

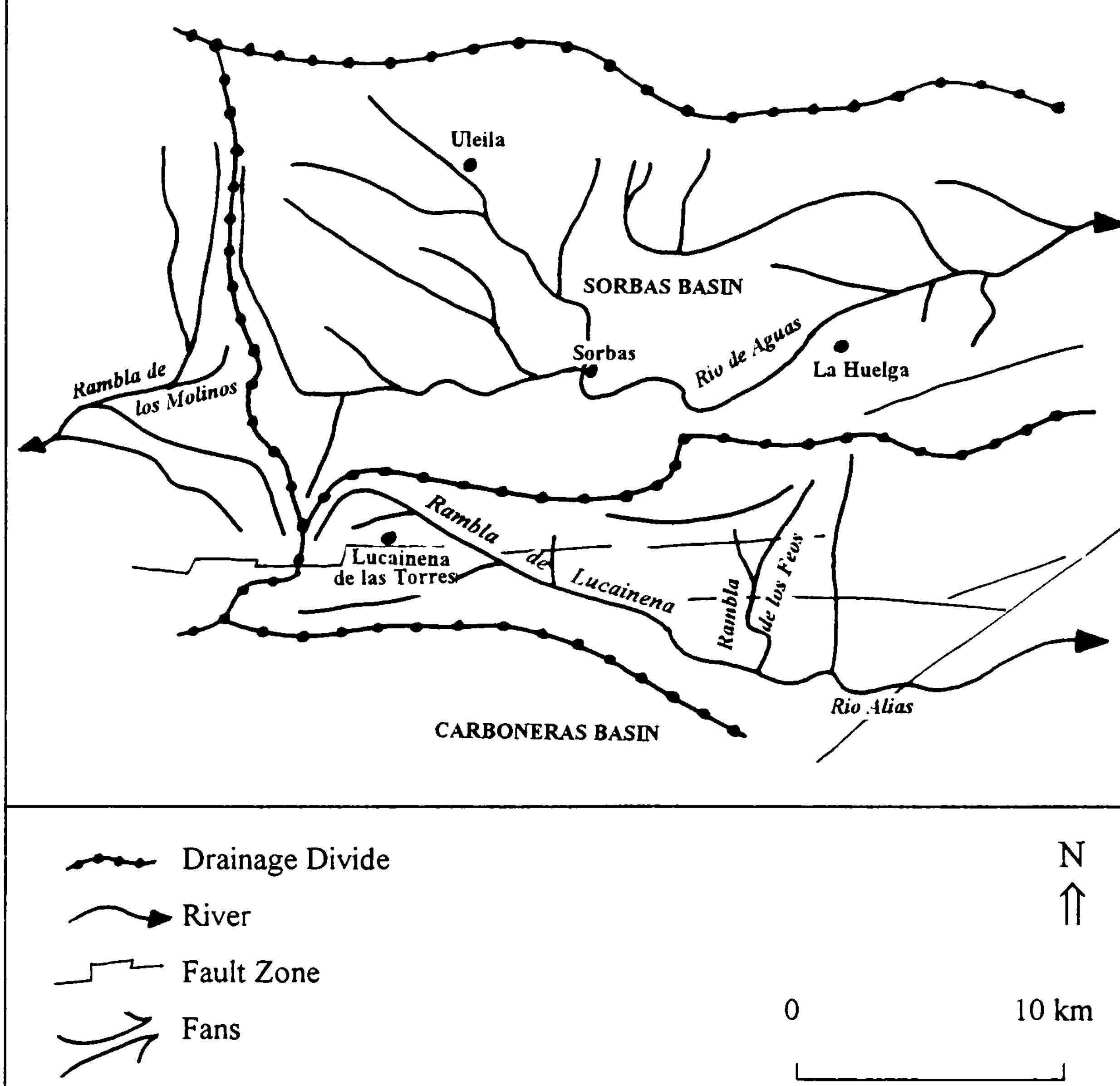


Fig. 1.4 The changing drainage pattern of the Rambla de Lucainena from the pre-Quaternary through to the present day. A-C show key stages in the drainage evolution.
Adapted from: Mather & Harvey, 1995

Evidence for this capture is provided by a reduction in sedimentation within the Sorbas Basin during this time and also a change in the sedimentology resulting in the loss of material derived from the Sierra de Alhamilla (Mather, 1993b).

The captures which began in the late Pliocene/early Pleistocene are still proceeding today at the western limit of the Rambla de Lucainena drainage. The history of this past drainage development is recorded by the landforms and abandoned terrace deposits left within the current drainage basin.

Current Drainage

The present headwaters of the Rambla de Lucainena flow from the southern margin of the Sorbas basin where Tortonian marls, sands and conglomerates crop out (Fig. 1.5). Just east of Lucainena de las Torres the Rambla cuts through the Northern Boundary Fault Zone and the fault zone breccias associated with it. Downstream the river cuts into the Palaeozoic-Triassic basement of the Sierra de Alhamilla which separates the Sorbas basin from the Carboneras basin. The junction between these two lithologies occurs just above the confluence of the Rambla Honda with the Rambla de Lucainena. The Rambla Honda is the largest tributary of the Rambla de Lucainena and drains through the metamorphic phyllites, schists, and sedimentary limestones and dolomites of the Sierra de Alhamilla basement which have a major influence on the downstream provenance of the Lucainena catchment. Farther down river the Rambla de Lucainena cuts through the Messinian calcarenites of the Azagador Member (the stratigraphy of which has been discussed by workers such as Martin and Braga, 1994), and at its farthest extent the river cuts into the marine marls, sands and limestones of the Messinian and the overlying Plio-Pleistocene gravels and conglomerates. It is from this point in the sequence that the Rambla de Lucainena started its westward incision (Mather, 1993b).

The aggressive headcutting and incision of the Rambla de Lucainena during the Pliocene and Pleistocene is recorded by a series of river terraces located on either side of the river. Study has identified 4 generic terrace groups associated with the Rambla de Lucainena drainage each of which will be discussed in subsequent chapters.

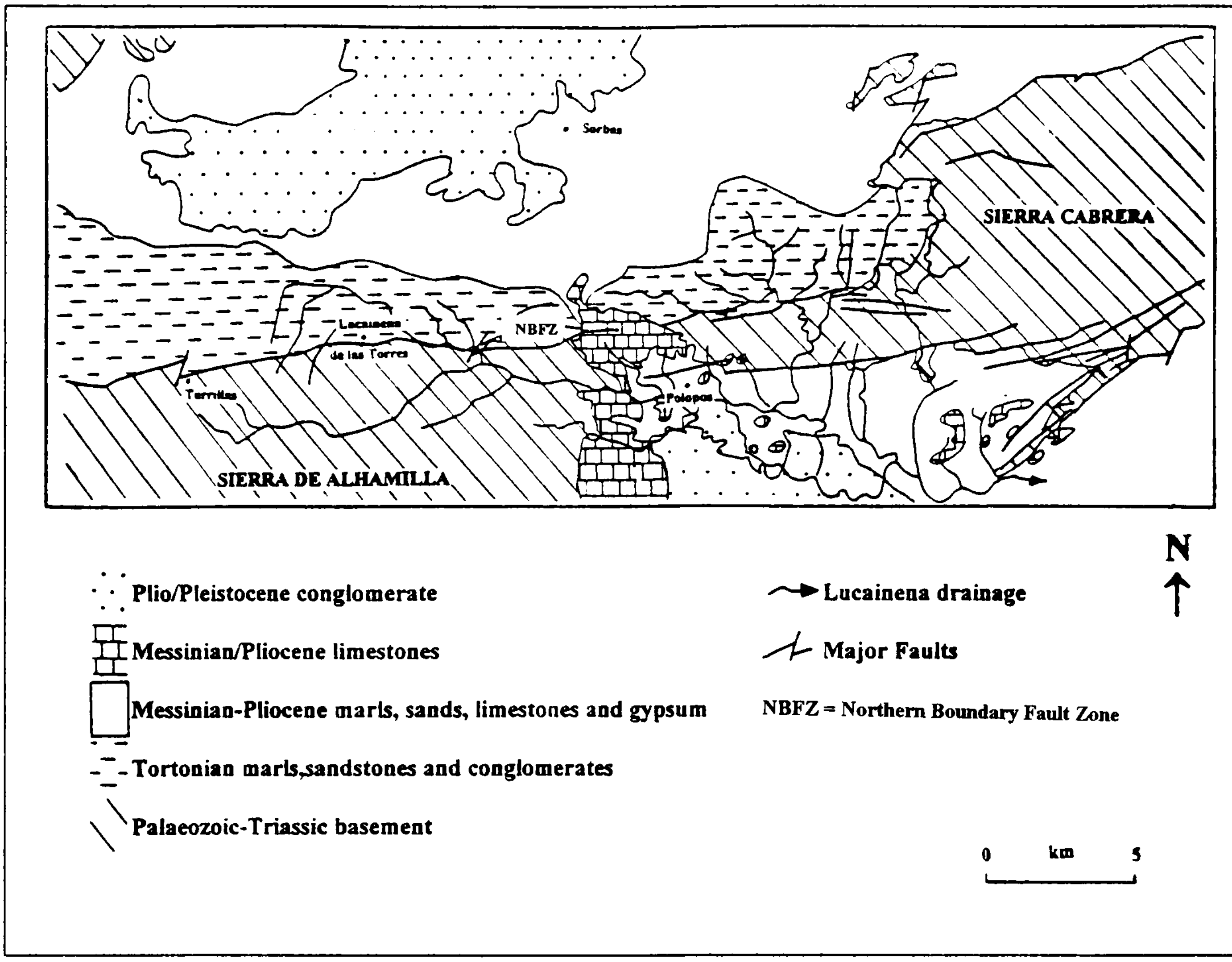


Fig. 1.5 Geological setting of the Lucainena catchment
Adapted from: Harvey & Wells, 1987

1.1.4 Climate

SE Spain has an unusual climate when compared with the rest of Europe. The classic Mediterranean climate is supposed to consist of hot summers and mild winters with low precipitation, but the rainfall in SE Spain is sometimes lower than 200 mm, suggesting an even more arid climate. Almeria is the driest region in Spain, its mean annual rainfall has been recorded to be as low as 120 mm (Geiger, 1970) although there has been great variation over the years with a maximum of 552 mm in 1989 (Capel Molina, 1990). This annual variation is reflected even more poignantly in weekly and daily records where extreme fluctuations can be identified. The precipitation is mainly seasonal with infrequent but extreme storm events in autumn and spring months. The winter and summer months are considerably drier with drought conditions prevailing in the summer months.

Temperature varies greatly across the province and between seasons. Generally the winters are mild and the summers are hot. The temperature and precipitation are due to the proximity of the Mediterranean Sea and the southern latitude as well as the other climate controls suggested by Capel Molina (1990) including proximity to the Atlantic Ocean and North Africa, rain shadow of the Sierras and depression tracks over the Atlantic Ocean and the Mediterranean Sea.

The climate during the Quaternary is assumed to be very similar to the present climate, being semi-arid with intense seasonal fluctuations (Rohdenburg & Sabelberg, 1973) which became more arid during European Glacials (Harvey, 1990).

The river basins within this region are mainly dry bed and subject to intermittent flash-flooding events as a result of these extreme climate conditions. The geomorphic processes are probably a combination of the climate and geology of the region.

1.1.5 Landuse

There has been a human influence in SE Spain since Neolithic times although the landscape impact of human inhabitation has become more prevalent in recent years (Vita-Finzi, 1969; Gilman & Thornes, 1985). This is predominantly due to grants provided by the government to encourage the re-development of areas previously considered to be too arid for agriculture (Mather, *pers com.* 1994). This has led to a dominance of artificial terraces across the landscape covering large areas within basin areas and the middle and upper slopes of the Sierras. This has had a substantial impact on this study as there has been some utilisation of Quaternary terraces, which can alter the form of the terrace and the introduction of man-made terraces which can complicate the story.

Many of the farmers within the Lucainena catchment also keep goats which they move from one area to another to graze. The trampling of goats across an area increases erosion which has significance in determining the rates of erosion for the contemporary part of this study (section 3.2).

Mining has also been prevalent in the area but only affects localised areas. There has been mining in past years in the vicinity of the Rambla de Lucainena especially in the area above Lucainena de Los Torres where there is a siderite mine. There has also been evidence of gravel quarrying within the river beds of the Lucainena catchment which was witnessed during the period of the study. Although this was only identified on a small scale this could influence the form and process of the current Lucainena drainage.

Roads have also had an influence on the morphology of the landscape despite the small population. Their main impact on this study is due to road cuttings through several Quaternary terraces within the Lucainena catchment. These cuttings can deform or cause degradation to the sections but, on the whole are beneficial to the study because they expose sections or detail which could not previously be determined.

Human influence on the Quaternary sequences of the Lucainena catchment is minimal but man's impact on altering the landscape since then is of great significance.

1.2 RECONSTRUCTION OF PALAEODRAINAGE HISTORY

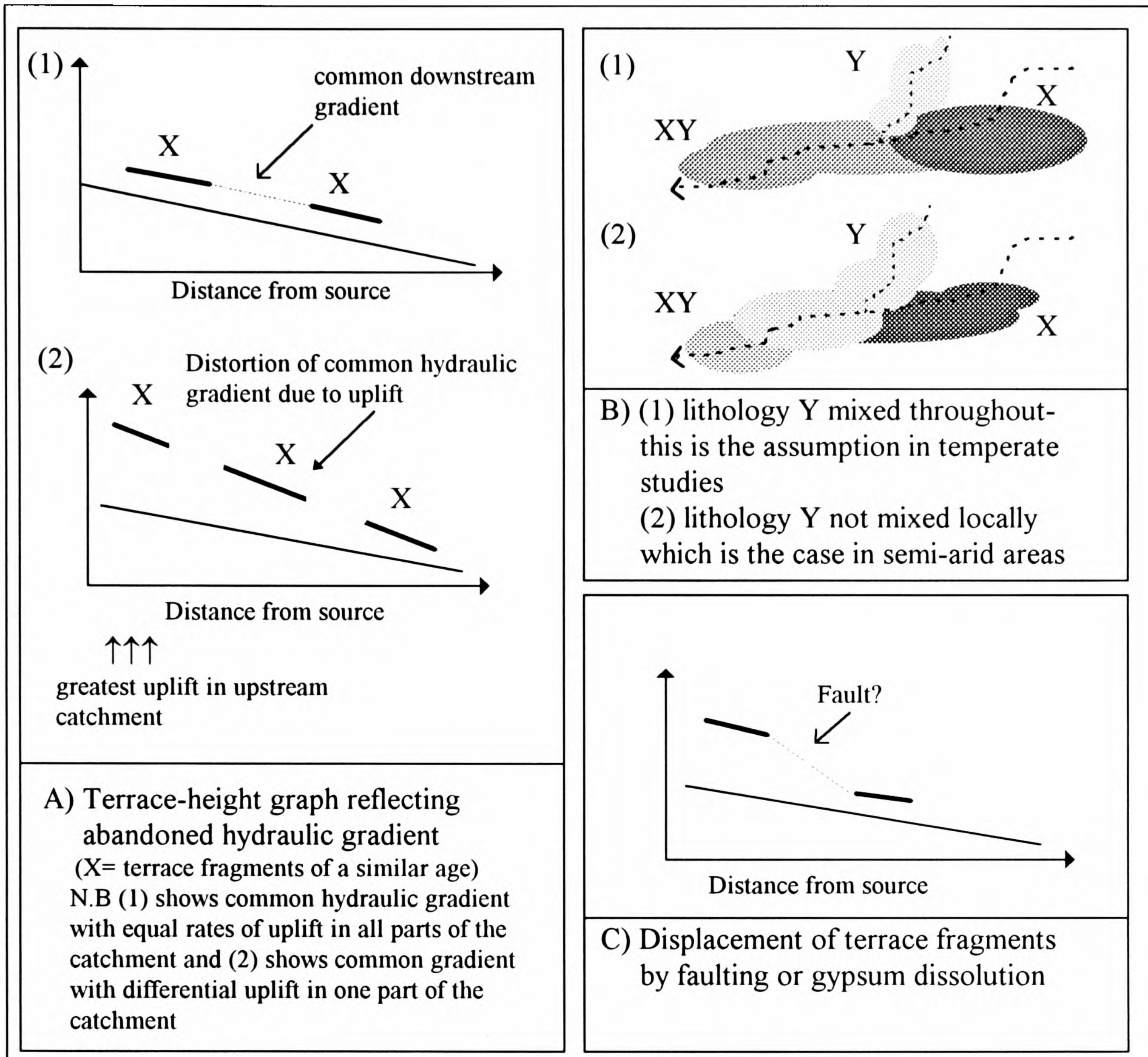
The reconstruction of palaeodrainage history from fluvial landforms and sediments has focused primarily on temperate regions. Here climate and sea-level change have left a complex record of Glacial and Interglacial fluvial systems (Bell & Walker, 1992; Lowe & Walker, 1997). These systems have been extensively studied and provide some of the most detailed palaeoenvironmental data for the Quaternary (Jones & Keen, 1993). The aim of these studies is not only to reconstruct changing drainage patterns, but more importantly to document patterns and rates of environmental change. In contrast, drainage reconstruction in tectonically active arid and semi-arid areas has received relatively little attention (Cooke *et al.*, 1993). The work that has been done has concentrated on understanding the role of neotectonics in drainage evolution, and has to a certain extent ignored the potential information that these river systems contain about environmental change (e.g. Mather & Harvey, 1995; Harvey & Wells, 1997).

In both temperate and semi-arid regions drainage history is recorded by flights of fluvial terraces and a range of sedimentary deposits. There are two primary goals in investigating this evidence: (1) to identify, record and correlate fragments of river terraces or sediment of similar age using the tools of lithostratigraphy and biostratigraphy; and (2) to interpret the palaeoenvironmental significance of these fragments and sediment accumulations.

In temperate regions terrace correlation is normally achieved by a combination of height, sedimentology and provenance studies. Sediments deposited within a single fluvial system during a given time period should reflect the common characteristics of the fluvial regime and of the catchment in which they were deposited. For example, clast lithology should reflect those rock types which cropout within the catchment, up stream of any given point. Consequently, clast lithology is widely used in temperate studies as a method of correlation (Green & McGregor, 1980; Green, Hey & McGregor, 1980; Green, McGregor & Evans, 1982; Green & McGregor, 1983; Bridgland, 1986; McGregor & Green, 1986; Green & McGregor, 1987). Equally, terrace fragments of similar age should have a common down stream gradient reflecting the rivers base level at the time (Fig. 1.6A). Although often far from straight forward it is possible, using a combination of sedimentology and morphology, to identify and correlate terrace fragments of similar age. The fluvial facies and the biological remains they contain are then used to provide information about the palaeoenvironment. The detail and sophistication possible in this type of study is well illustrated by the work on the gravel and terrace deposits of the River Thames in Britain (Gibbard, 1985; Bridgland, 1988; Bridgland, 1994; Gibbard, 1994; Gibbard & Allen, 1994).

In contrast semi-arid regions pose more of a problem, and one which has been poorly explored to date. In semi-arid regions the drainage system does not necessarily form an integrated system. For example, local rain storms may affect single tributaries and integrated channel flow through out a river system is rare. This makes correlation on the basis of clast lithology difficult since downstream mixing and distribution of lithologies need not occur (Fig. 1.6B). As a consequence correlating terrace fragments on the basis of provenance, sedimentology and morphology becomes difficult. The extent and significance of these problems have not been fully explored. Furthermore, when the picture is complicated, as it is in SE Spain by neotectonics and subsidence induced by the solution of subterranean gypsum (Mather, 1991; Mather & Harvey, 1995) the problems become even greater. For example, differential uplift within a catchment may cause terraces of similar age to be elevated to different levels (Fig. 1.6C; Harvey & Wells, 1987; Petts & Foster, 1990), equally subsidence induced by the solution of gypsum may alter terrace heights (Fig. 1.6C; Mather, 1991). Despite these types of problems drainage reconstruction has been attempted in a number of regions, perhaps most notably in the Sorbas basin of SE Spain. Here the outline history of drainage evolution has been well determined (Harvey & Wells, 1987; Mather, 1993a; Mather, 1993b; Mather & Harvey, 1995), and its link to the geological and tectonic evolution of the area established. However, beyond reconstructing the drainage evolution the palaeoenvironmental significance of the evidence has not been fully explored as a means of understanding, for example, climate change in the Quaternary. The potential of this type of fluvial study to provide such information in semi-arid areas needs to be explored further.

Another area of concern is that previous work has been polarised between palaeodrainage reconstruction (e.g. Harvey & Wells, 1987; McIntosh *et al.*, 1990; Chatters & Hoover, 1992) and modern process work (e.g. Thompson & Campbell, 1979; Hey & Thorne, 1984; Hey, 1986; Harvey, 1991; Ashmore, 1991; Benn & Erskine, 1994). The aim here is to integrate these two aspects by making contemporary observations which will assist in the interpretation of palaeoevidence. This integrated approach will help to resolve some of the problems encountered with terrace correlation in tectonically active semi-arid regions.



A) Terrace-height graph reflecting abandoned hydraulic gradient (X= terrace fragments of a similar age) N.B (1) shows common hydraulic gradient with equal rates of uplift in all parts of the catchment and (2) shows common gradient with differential uplift in one part of the catchment

B) (1) lithology Y mixed throughout- this is the assumption in temperate studies (2) lithology Y not mixed locally which is the case in semi-arid areas

C) Displacement of terrace fragments by faulting or gypsum dissolution

Fig. 1.6 A schematic diagram representing some of the methods and problems of terrace correlation.

It is with this background that a series of objectives for the current study has been identified, these are listed below:

(1) To make a preliminary assessment of the problems associated with drainage evolution studies in semi-arid regions, due to the lack or absence of fluvial integration which normally exists in temperate regions, and to assess the importance of variation in

catchment erodability and storage. Both of these aspects have the potential to effect the ability to correlate terrace fragments on the basis of terrace elevation and clast lithology.

(2) To reconstruct the drainage history of the Rambla de Lucainena using geomorphological and sedimentological evidence within the drainage basin.

(3) To assess the potential of the Rambla de Lucainena to provide information about palaeoenvironmental change during the Quaternary within this region of SE Spain.

These three objectives are reflected in the structure of this project. The next chapter, 2.0, outlines the methodology required to achieve these objectives. This methodology falls into two sections, data collected to achieve objective 1, contemporary data; and data collected to achieve objective 2, Quaternary data. The collection of contemporary data concentrated on 2 key aspects: (1) erosion rates and channel storage capacity of key lithologies within the catchment; and (2) tributary dynamics and their effect on downstream bedload mixing. These were identified as important issues within the catchment for 2 reasons, firstly erosion rates can affect sediment productivity and hence may have some significance in explaining the relative abundance of certain lithologies within Quaternary terrace fragments. Secondly, since in semi-arid areas the climate may be very local, integrated channel flow is rarely achieved, this inhibits downstream sediment mixing and as a consequence the tributary junctions can be associated with anomalous clast concentrations (Schumm, 1972). The importance of both in complicating Quaternary drainage evolution has not been explored and could be of potential significance.

The subsequent chapters 3.0 and 4.0 deal with the contemporary and Quaternary data respectively. Chapter 5.0 integrates the Quaternary and contemporary data and attempts to unravel the complex drainage history of the Rambla de Lucainena and make suggestions about the palaeoclimatic significance of some of the key events within its evolution.

2.0 METHODOLOGY

The project falls into two unequal parts: (1) contemporary process studies to determine the relative erosion rates of key lithologies and the significance of bedload input from tributary intersections; and (2) Quaternary terrace analysis to determine the drainage evolution of the Rambla de Lucainena and its palaeoenvironmental significance. For this reason the layout of this chapter reflects this structure, with the methodology used for the contemporary process observations presented first and then a discussion of the methodology used for determining the palaeodrainage evolution.

2.1 CONTEMPORARY PROCESS OBSERVATIONS

Contemporary process data were collected to provide information on: (1) the erodability of different lithologies within the catchment; and (2) the modern fluvial system.

2.1.1 Methodology

A: Determination of the rate of erosion of different lithologies

Contemporary field data were collected to determine the relative erosion rates of the predominant clast lithologies within the Lucainena catchment. The collection of these data had two aims:

(1) To provide data on the rate of slope modification and sediment productivity.

(2) To provide data on the erodibility of different lithologies in order to assist in the interpretation of lithological abundance and provenance data in the terrace fragment.

Three sites were identified for contemporary analysis in which a series of erosion plots and checkdams were installed to record data on erosion and sediment bedload transport.

Site Selection

The predominant clasts found within the Quaternary terrace fragments were basement schists and phyllites, Triassic limestones and dolomites, Tortonian limestones, sandstones and conglomerates and Pliocene limestones, sandstones and conglomerates. Therefore, to assess the relative erosion rates of the main sediment sources within the Lucainena catchment it was necessary to set up four sites, in the basement schist, the Tortonian sediments, the Triassic limestones and dolomites and in the Pliocene sediments. The sites chosen needed to be representative of these four main lithological types. In addition, possible sites were eliminated if they did not meet the following criteria:

1) Accessibility-so they could be checked regularly
2) Unpopulated area-so they wouldn't be subjected to any external interference
3) Catchment size
4) Ability to install erosion pins and checkdams.

It was decided that each site should have a minimum of two erosion grids on opposite slopes, a check dam and a raingauge in order to give the basic data required. Several potential sites were eliminated according to these criteria, leaving just 3 sites remaining. Unfortunately a site could not be found within the Pliocene sediments because all of the incoming tributaries consisted of hard sediments with no weathered regolith, which were impossible to hammer pins into. Therefore, only three controlled sites were set up in each of the main lithologies, basement-schist, Tortonian and Messinian (reworked Triassic). Each site was picked because it exhibited characteristic features of each of the lithologies and fulfilled the designated criteria. Sites were set up on the characteristic sparsely vegetated slopes on both easterly and westerly aspects. Care was taken to make sample size representative and comparable across sites. Each site has a minimum of two grids and two profiles, a check dam and a raingauge. For full site details see Table 2.1.

Even though the sites chosen for contemporary data selection were located where there would be limited disturbance by both people and animals it was impossible to avoid this altogether. For this reason the data was limited by the fact that pins became dislodged or removed and in some cases were affected by small brush fires.

SITE	Site Description	Erosion Pin Grid	Erosion Pin Profile	Sediment Trap	Rain Gauge	Stone Tracers
A-Tortonian catchment	NW & E facing slopes Marls Poorly vegetated	2 on opposing slopes	2 on opposing slopes	✓	✓	✖
B-Schist catchment	N & SE facing slopes schists Well vegetated	2 on opposing slopes	2 on opposing slopes	✓	✓	✓
C- Messinian catchment	E & W facing slopes Basal Messinian conglomerate of Triassic carbonate rocks Poorly vegetated	2 on opposing slopes	✖	✓	✓	✖

Table. 2.1 Contemporary site details

Erosion Profiles and Grids

Two main methods of direct erosion measurement have been used in scientific studies of this nature, erosion pins hammered into the ground at regular intervals (Schumm, 1956; Haigh, 1977; Sala, 1988) and erosion frames supported by four corner pins (Campbell, 1970; Mosley, 1975; Benito *et al.*, 1992).

For the purpose of this study erosion pins were preferable to the erosion frames because they were easy to use, cheap and could be set up in all of the site localities. The erosion frame would have been difficult to construct and set up as it requires four correctly aligned corner pins to rest on, it would also have been heavy to carry, more expensive and unsuitable for steep or uneven slopes. A more recent invention which could have been used is the Profiler described by Wells and Bennett (1996) which uses two permanent support pins which are returned to at regular intervals for the ground in-between to be profiled. However, if one of these support pins is removed or disturbed the erosion data for that period is also lost and the pins need to be reinstalled and the site re-profiled before erosion measurements can continue. The same is true if a corner pin to an erosion frame is removed. If this happens to an erosion pin then only the erosion measurements for that particular pin are lost, all of the data from the other pins remains and the disturbed erosion pin can be quickly reinstated.

The main disadvantage of erosion pins are that they interfere with the natural slope processes and may disrupt the superficial crust when installed. However, the same can be argued of the support pins used for both the erosion frame and profiling device, and because only relative erosion data was required for this study the errors incurred due to these influences were considered acceptable.

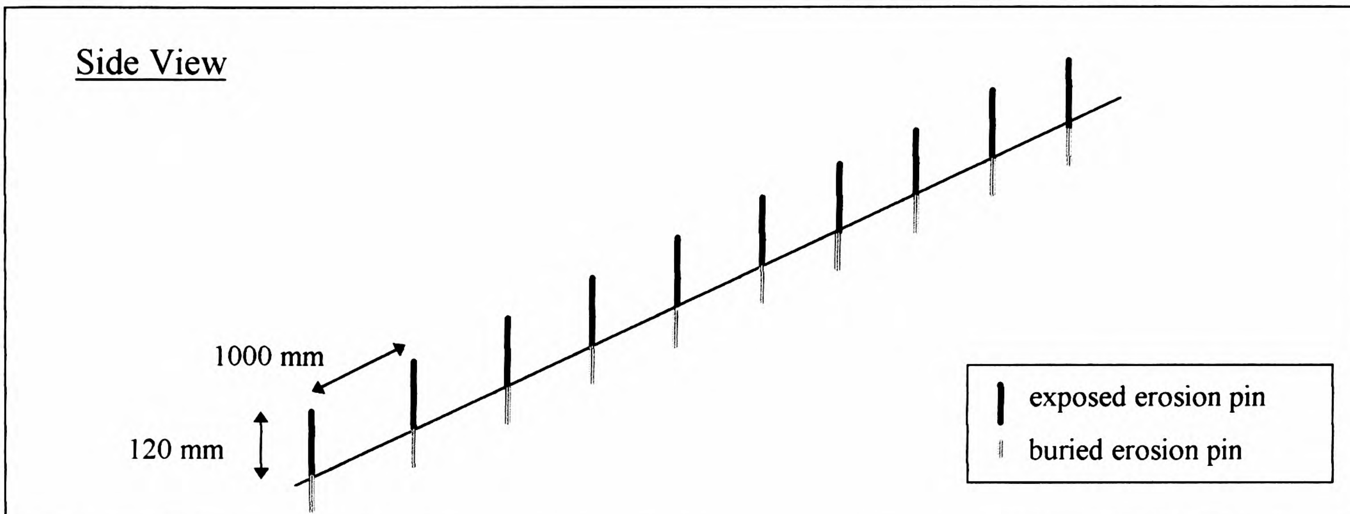


Fig. 2.1 Erosion Profiles

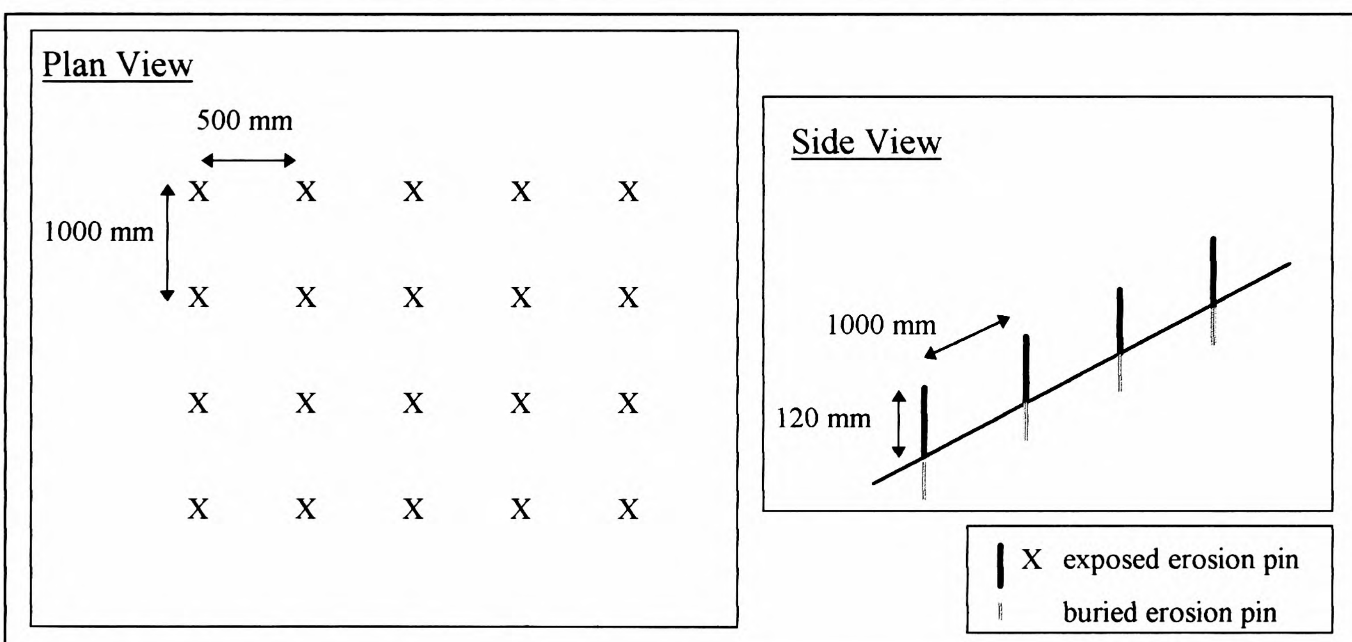


Fig. 2.2 Erosion Grids

Erosion pin profiles were set up with both easterly and westerly aspects on sparsely vegetated slopes (Fig. 2.1). The 250 mm pins were hammered in vertically, leaving 120 mm of the pin exposed. They were spaced 1m apart. The slope for each of the pins was profiled, using an abney level, once the pins were installed and at the end of the study period. Grids of pins, 5 by 4, were also set up at each of the sites (Fig. 2.2), on opposite slopes, in four rows a metre apart with five columns 500 mm apart. The pins were again hammered in vertically leaving 120 mm of each pin exposed. Every set of pins was measured each field season, every 2 to 3 months over a period of a year. Additional pins were installed in areas of interest, such as areas of potential capture and small channels. Again these were measured during each field season to monitor any changes.

Checkdams

Each site had a check dam installed just above the junction between the tributary and the main river. These were installed to give an idea of the frequency of sediment transport and the quantity and nature of the sediment transported. The checkdams were pits cut into the channel bed, they were generally 1 to 2 m in length, 0.5 m in depth and width (Fig. 2.3A). They were carefully positioned at points where the channel had widened, this was because the increase in channel width would lower the velocity and hence, would be a point where some deposition of load would be expected. The pits were covered in thick plastic sheeting to keep the shape of the dam and to provide a base at which to measure future sediment accumulation. The lips of the plastic were buried and weighted down with stones. Checkdams were checked for sediment accumulation at each field seasons. When sediment had been deposited the checkdams were photographed (Fig. 2.3B) and sediment was removed, weighed and recorded.

Raingauges

To accompany the erosion pins and checkdams simple raingauges were installed to provide information on the microclimate. They also provided information on the minimum rainfall required to move a volume of sediment. They were buried to about half their depth on unvegetated slopes at each of the sites. However, they proved to be limited in success, as due to their nature they were easily broken or kicked over by animals.

Painted Tracers

At one of the sites clasts on one slope were painted orange to enable future identification (Fig. 2.4). At each visit the stones were photographed from the same point to monitor the progress of the stones. When extensive movement was noticed minimum movement was measured. This enabled a greater understanding of the rates of transport. This method was not suitable at all sites due to the nature of the differing lithologies.

(A)

(B)

Fig. 2.3 An example of the checkdams installed at each of the contemporary sites. This particular site is the Messinian catchment and shows (A) the checkdam empty at installation (September, 1994) and (B) the checkdam filled to capacity (April, 1995). The spade in the photo is 1 m long.

Fig. 2.4 Painted tracers within the schist catchment
The width of the photo represents 1 m.

B: Examination of characteristics of contemporary channel

Basin form

To enable the comparison of the findings of this study with those of other areas it was necessary for the description of the following characteristics to be made:- drainage area, drainage density, drainage pattern and stream order. Maps on a 1:50 000 and 1:25 000 scale and air photos on a 1:30 000 and 1:12 000 scale were used in the desk study phase of this project to enable the description of these characteristics. The Lucainena drainage basin was delineated by deciding on the location of the drainage divides. This was done by ascertaining the landform characteristics and the drainage extent from the air photos. Once this had been decided on the drainage area was established. Area is one of the most important drainage characteristics because almost every watershed feature is related to it. Stream order is another important property which can be used to describe a drainage basin. Several methods exist for calculating this, the most commonly used are the Strahler and Shreve methods (Richards, 1982). The one favoured for this study is the Shreve method which unlike the Strahler method is changed by the addition of tributary streams of a lower order (Petts & Foster, 1990). The segment ordering is achieved by each outer link or first order stream being given a magnitude of one and each subsequent link being equal to the sum of all the previous links (Fig. 2.5).

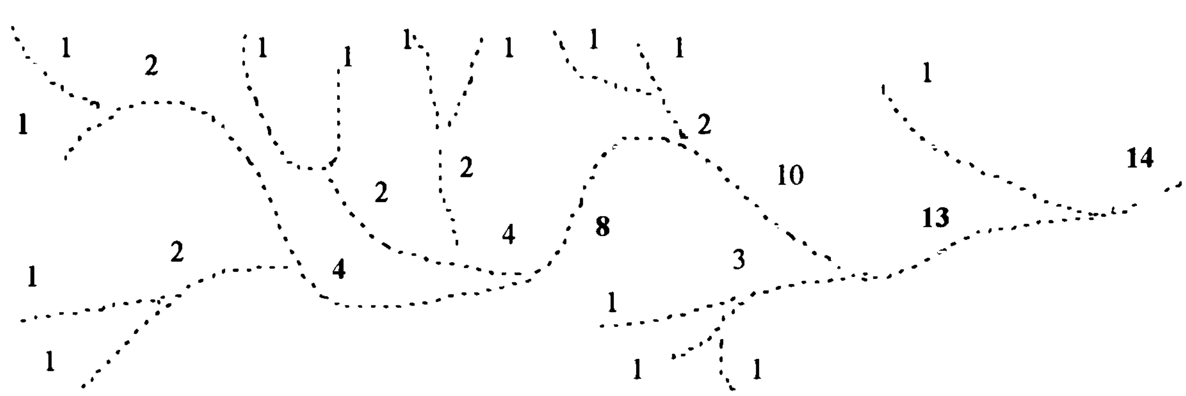


Fig. 2.5 The Shreve method of establishing stream order
The stream order in this example is equal to 14

Several methods exist for ascertaining the density of the drainage network, the simplest of which is to calculate the length of the streams per unit of drainage area. The drainage pattern was determined by identifying the angle of intersection of the tributaries with the main drainage channel. This desk study was followed up by field analysis of the contemporary basin form and processes.

The analysis of the basin form was limited by the age and accuracy of the maps used to compile the data. Air photos were used to help provide more detail and improve the accuracy. However, as the maps would have been drawn up from air photos there was little scope for improvement, so where possible ground truthing was attempted in the field.

Tributary significance

Bridgland (1986) noticed that there has been little application of clast counting techniques to the gravel bed-loads of modern rivers. He suggests that studies of this type would be extremely beneficial, especially the effects of tributary input and downstream distance travelled before such inputs are completely mixed with the bedload of the main river. From preliminary analysis it was clear to see that the input from tributaries sometimes had greater importance than that of the main channel within the Lucainena catchment. This would have importance not only in determining the contemporary processes at play in the catchment but also on the presence of sediments within some Quaternary landforms. Specifically it might help to explain the higher levels of a particular lithology found within the same terrace level as being the result of increased input of a certain lithology from a tributary junction. To assess this counts of contemporary clasts (n=100) within the main river channel were undertaken above and below tributary confluences and a visibly important tributary was chosen for more detailed analysis. This was to provide further information on the significance of sediment input from the major tributaries. It also provided a key insight into the provenance of some of the Quaternary terrace groups. This is because the provenance of the present drainage is known and the abundance of particular lithologies can be established and related to the abundance and provenance of Quaternary terrace sediments.

To identify the significance of sediment input from tributaries photographs were taken where contrast between tributary and main channel bedload could be seen. Further analysis included grab samples taken before and after tributary junctions followed by sampling from trial holes which were deep enough to avoid collecting material from the weathered zone. Channel width was also measured above and below tributary intersections to identify whether sediment build up at these junctions was having any significant influence on the channel morphology.

2.2 DETERMINING THE PALAEODRAINAGE EVOLUTION

The individual stages in the development of the Lucainena drainage basin are recorded within the Quaternary terrace remnants associated with the past river level. To determine the key stages in this development the information recorded within these terrace remnants needed to be unravelled. This entailed field investigation to identify generic terrace groups by elevation and sedimentology. The correlation of terrace remnants was achieved, where possible, on the basis of continuity, relative elevation and stratigraphic relationships (Leopold, Wolman & Miller, 1964). Where appropriate sedimentary features, fossil flora and fauna and palaeosoils were also used to aid correlation.

2.2.1 Methodology

Each generic terrace group represents a stage or an important event within the Rambla de Lucainena's drainage history. Therefore, the first requirement of this project was to record, correlate and document each terrace remnant within the Lucainena basin. This was achieved through the morphological, sedimentological, geochemical and palaeontological characteristics of each terrace fragment within the drainage basin.

A: Morphological Evidence

Aerial photographs at a 1:30 000 and 1:12 000 scale for the area were used to provide the preliminary data for this project enabling the identification of key geological and geomorphological features to be investigated in the field. These photos also provided a useful locational tool whilst collecting field data and enabled corrections to be made to the maps where appropriate.

Individual terrace fragments were mapped in the field on to 1:10 000 base maps. Their height above the present river bed was recorded along with their sedimentological characteristics and clast distribution. Heights were determined using an abney level which provided a reasonable level of accuracy whilst also being lightweight and quick to use. The heights were measured to the base and top front and back of each terrace fragment. Where terrace fragments had considerable lateral extent several points were measured along its length. These heights were then converted to heights above sea level and put onto a height distance graph, showing elevation above sea level against distance from source. Difficulty arose when determining the distance of the fragment from the source of the drainage, as data is conventionally plot in one of two ways (Kirkby, 1969);

either: (1) projection of terrace fragments at right angles on to a straight line of best fit along the river course (Fig. 2.6A); or (2) projection of the terrace heights onto the contemporary river profile (Fig. 2.6B).

The first method is generally preferred because it is the easiest to use, however, it does have several limitations. The first problem is that the projected base line will have a different gradient to that of the actual river profile. This has the potential to cause problems with correlation, as terrace fragments of similar age could appear at different levels above the river profile. In addition, where the river has a sinuous course, projection of terrace fragments onto a line of best fit may alter the relative position of terrace fragments, causing problems of overlap, especially where the terrace fragments are closely spaced in height. In theory, to overcome these problems a separate projection base-line should be constructed fitting the river course occupied during the formation of each terrace level. Obviously this is not practical because the river course cannot be established until the terrace level has been identified.

The second method assumes that the palaeo-river course is the same as the existing river course, which is clearly not always the case. This can cause problems particularly with older terrace fragments.

Therefore, Kirkby (1969) suggests that, graphical analysis should probably include at best, a projection of oldest terrace fragments onto a straight line of best fit, and a projection to the contemporary river course for the most recent terrace fragments. Due to the small time spanned by the Rambla de Lucainena's drainage development and the close height spacing of the terrace groups most of the terrace fragments have been projected onto the present river course. The oldest terrace fragments were also projected onto a south-west to north-east line of best fit to see if better correlation could be achieved.

B: Sedimentological Evidence

Sedimentological characteristics were often traceable between terrace fragments and frequently allowed a more positive identification of terrace levels than just the height clustering alone. The sedimentological observations recorded included: lithology, grainsize, sorting, sphericity, sedimentary structures, macro- and micro- fossils. This not only helped to provide information about the continuity of a surface but also provided data on the provenance of the terrace deposits and the palaeoenvironment in which it was deposited.

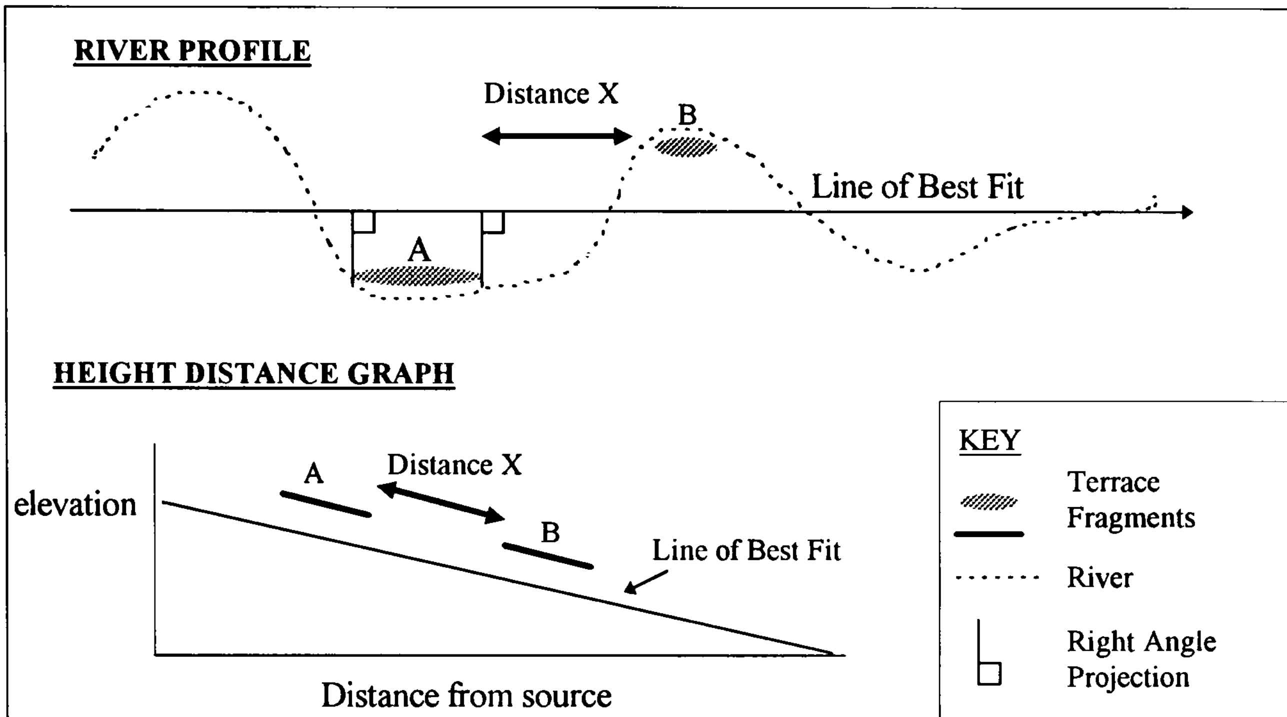


Fig. 2.6A Method 1: Projection of terrace fragments onto a line of best fit

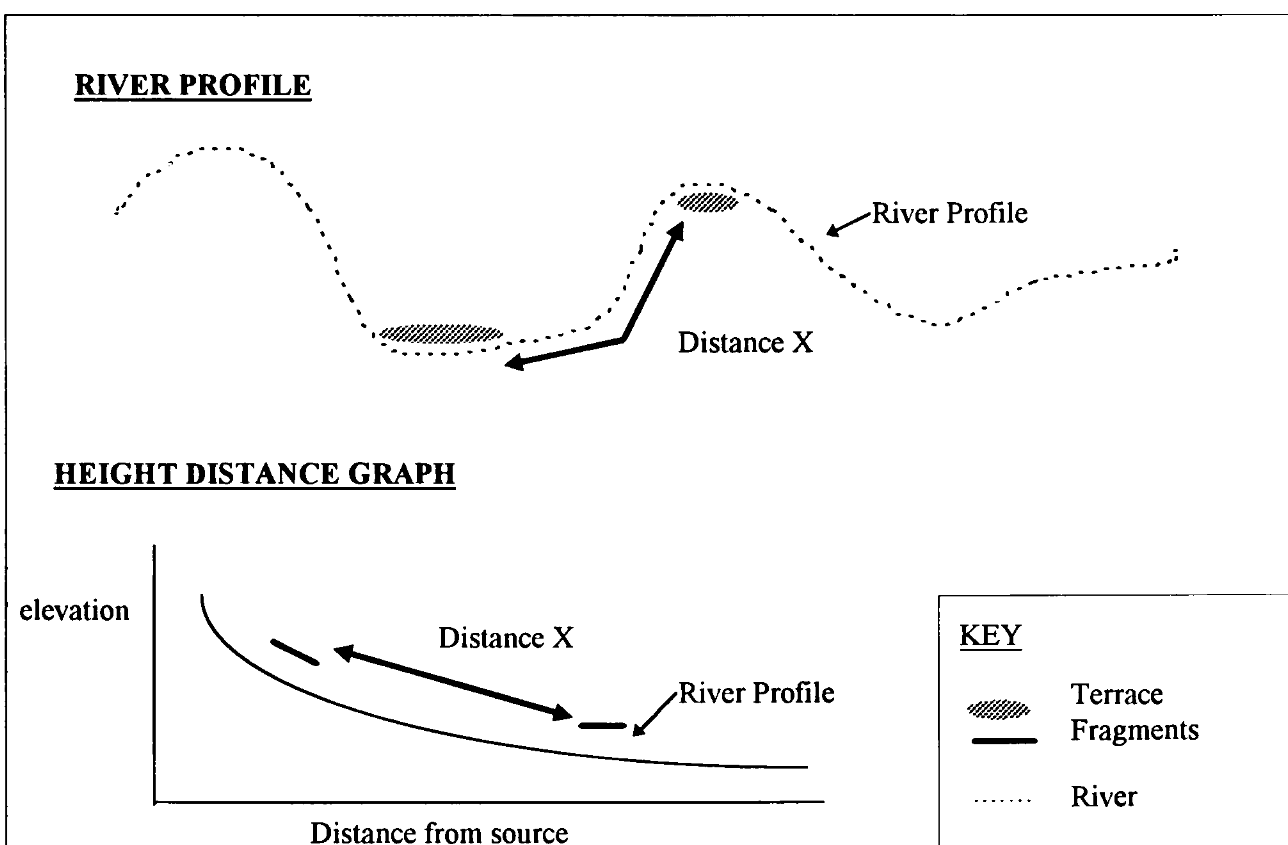


Fig. 2.6B Method 2: Projection of terrace fragments onto the contemporary river profile

Sedimentological characteristics are useful for the purpose of terrace correlation but may need to be used with caution in semi-arid areas for the reasons discussed in section 1.2.

In addition to observations on each terrace fragment, logs were measured at key exposures to provide more detail about the sediments and their importance. The logs were lithological profiles recording individual beds and their sediment characteristics including: grain size, colour, sphericity and sorting. Palaeocurrents were also measured where possible from clast imbrication and recorded on the logs. These were used where possible to determine the direction of flow for each terrace deposit and for the reconstruction of the palaeodrainage at the time of deposition. Where thick beds of fines were recorded, samples were taken and the position of these samples recorded on the logs. In order to determine the provenance of fine grained fractions, particularly when they dominated a section, samples were taken for geochemical analysis.

Clast characteristics were determined from the gravel beds of each terrace fragment from in situ samples. At each site a random sample of 250 clasts were taken, although at smaller exposures this was reduced to 100. Sample size is based on that recommended by Bridgland (1986). For each clast the following was recorded: (1) Lithology; (2) 3 orthogonal axis; a, b and c. The former was used to establish a clast distribution for each terrace group and the latter was used to determine average clast size, particle form and sphericity. Average clast size has been established by collating the frequency of different sizes of b-axes and was then used to make an estimation of relative velocity of sediment deposition. Particle form was determined via ternary particle form diagrams constructed using Hockney's (1970) modification to the co-ordinate system of Sneed and Folk (1958). Particle sphericity was established using Krumbein's sphericity index (Briggs, 1981) determined by the formula: $\psi = \sqrt[3]{(bc/a^2)}$. The sphericity values range from 0 to a maximum of 1, where a true sphere has a value of 1.

The clast counts provided a detailed description of the lithological content of a deposit and the relative abundance of lithologies within each deposit. These were used to compare specific terrace groups and differentiate between deposits of different age.

C: Geochemical Evidence

Clast counts only revealed the lithological content of the coarse gravel fragments, therefore where terrace fragments also consisted of fine unconsolidated sediments, samples were collected for geochemical analysis. These were analysed to determine the provenance of the fines and to back up information provided by the clast count data. The samples were collected from trench sections to enable sampling from fresh exposures. Care was taken to minimise any cross contamination. Samples were dried overnight at 105°C. They were then ground down to a powder in a ball mill, 0.25g of each sample was weighed out on an accurate top pan balance to +/- 0.005g and then mixed with 1.25g of lithium metaborate. There is a slight possibility of errors when weighing the samples and a small possibility of cross contamination whilst drying and grinding, but with careful handling this was kept to a minimum. The powdered mixtures were then put into carbon crucibles and heated in an oven at 1000°C for 20 minutes. This fused the lithium metaborate with each of the samples leaving a hot molten residue. Once removed from the oven the molten samples were immediately tipped into beakers containing 150 ml of 3.5% Nitric acid. These beakers were put onto magnetic stirrers for an hour. The contents of the beakers were then tipped into 250 ml volumetric flasks and topped up to 250 ml with deionised water. The contents were poured into 100 ml bottles for analysis and the remainder discarded. The samples were then analysed using ICP-OES and ICP-MS. The ICP-MS used rock standards for calibration and the ICP-OES used synthetic standards. The ICP-MS analysed for common oxides whilst the ICP-OES analysed for rare earth elements. Whilst analysing the samples there was the possibility that the instrument will drift giving incorrect readings. This problem is reduced by introducing standards at regular intervals. When interpreting the results only the larger discrepancies were interpreted, as small differences can be attributed to the errors discussed above.

This method of provenance analysis was used in preference to the more commonly used technique of heavy mineral analysis (Morton, 1991) because it analyses for a greater range of elements and hence, provided more useful results. This technique has not been used before in provenance studies but could provide a valuable tool in future provenance analysis.

D: Palaeontological Evidence

Where macro-fossils were found they were identified and looked for in corresponding terrace fragments to try and aid correlation. They were on the whole treated cautiously as they were mainly reworked from older sediments and hence could be found in all terrace levels older than the sediments from which they were derived (i.e. all Quaternary sediments). Microfossils on the other hand provided a more useful tool despite the problem of reworking, due to their smaller size and rapid proliferation which meant they were found in relative abundance especially in some of the ponded sediments. Several areas were sampled in the hope of yielding microfossil evidence. The microfossils identified were useful in providing additional information on the climate and environment at the time of deposition.

Sample positions were located on log sections. Only consistent layers of fines were sampled, because it would be unlikely to find identifiable microfossils in coarser gravel layers. Care was taken to minimise contamination of the samples and the faces of exposures were excavated to obtain only fresh samples. Approximately a kilogram of sediment was collected for each sample to ensure adequate resources should a problem occur during processing. The processing technique was quite straight forward because the samples were predominantly soft fine sediments. The samples were mixed with water and then washed through a series of sieves to remove any clays and muds. Again care was taken to minimise contamination by a process of washing and dying the equipment with a blue dye prior to starting on a new sample. This would ensure that any microfossils trapped in the mesh from a previous sample would have a blue appearance and be discarded. The sieving left the samples divided into four sections of 1 mm, 500, 250 and 63 microns in size. The samples were then dried and stored in this form. The residues of the samples were picked using a binocular microscope and a plastic picking tray. Equal weights of each sample were picked to make the results comparable. The microfossils were sorted and mounted on faunal mount slides with 30 scored rectangles.

2.3 SUMMARY

This project has been accomplished by the use of both Quaternary and contemporary data collection techniques. Each type was collected in a very different way but with the overall aim of deducing the drainage development of the Rambla de Lucainena throughout the Quaternary. The Quaternary data collection has enabled the establishment of stages in drainage development through the identification of generic terrace groups correlated on the basis of relative elevation, sedimentology, palaeontology and geochemistry. The use of contemporary data has enabled a fuller understanding of these Quaternary landforms and the processes that led to their deposition. This type of two fold approach is essential for the full understanding of any palaeoenvironment because the present environment will reveal evidence which can be applied to the past one.

3.0 PROCESS DATA

The aim of this chapter is to present the results of the contemporary data analysis and to interpret the significance of these results in relation to the drainage development of the Rambla de Lucainena during the Quaternary. Contemporary process data are frequently ignored in studies of this type, but as will be shown can provide invaluable modern day analogues which can be used to provide insight into the processes which were happening during the deposition of Quaternary landforms.

The contemporary data were collected with the goal of achieving two aims: (1) to establish the significance of sediment input from tributary junctions on the sediment load of the main channel; and (2) to determine the relative erosion rates of key lithologies and hence, their significance as sediment sources in Quaternary landforms. This chapter will be split into three parts, the first will deal with the channel data and the second the erosion data. The third part will discuss the implications of these results for the determination of the Quaternary drainage evolution.

3.1 CHANNEL DATA

In temperate regions the link between dominant discharge of both a channel's cross-sectional geometry and planform has been well established (Schumm, 1981; Thorne & Lewin, 1982; Hey & Thorne, 1984; Fookes & Vaughan, 1986; Hey, 1986). However, this link is less apparent in semi-arid regions due to the transitionary and often very localised flow regimes. This has potentially important implications in reconstructing fluvial drainage history in semi-arid regions, and as such is explored in a preliminary discussion here.

Tributaries have a major impact on all fluvial systems, whatever the nature of the fluvial regime (Best, 1986; Best 1987; Best, 1988; Roy & Roy; 1988; Bristow *et al.*, 1993). However, in semi-arid areas where channel flow is often restricted to single tributaries due to the localised nature of storm events, their importance is even more dramatic (Best, 1986). This is especially true of fluvial systems such as the Rambla de Lucainena which do not exhibit a perennial flow in the main channel and are therefore relatively incapable of transporting large volumes of sediment.

In many respects the flow characteristics of rivers in semi-arid areas are analogous to what happens downstream of dams during flow regulation of rivers. Effectively flow regulation increases the importance of tributary bedload input downstream which is why this is comparable to semi-arid rivers. The literature on this subject is considerable (e.g. Petts, 1979; Petts & Thomas; 1986; Petts, 1987; Sherrard & Erskine, 1991; Gurnell *et al.*, 1994; Church, 1995), but is well illustrated by Benn and Erskine (1994) who investigated the complex channel response of the Cudgegong River below the Windamere Dam, in Australia. They compared the pre- and post- dam fluvial characteristics and bedload changes of the main channel. Before the dam was built they found that the tributaries were a major source of gravel input into the Cudgegong river, but due to the competence of the main channel flow this gravel was constantly reworked into the channel sediment during flood events, leaving little sediment build up at tributary junctions. In short the fluvial system showed a strong downstream integration. After the dam was built they found that the reduction in peak discharge and sediment storage by the dam had reduced the flow competence of the main channel meaning that the sediment being built up at the tributary junctions was no longer being removed and reworked into the main channel. Benn and Erskine (1994) discovered that this reduction in flow competence resulted in the formation of sediment bars at tributary junctions due to the deposition of coarse bedload, and the reduction in channel width (channel contraction) associated with these bars at the channel confluence (Fig 3.1).

In semi-arid areas storms may affect only a single tributary and rarely initiate continuous stream flow throughout the whole system. This means that the Rambla de Lucainena frequently has a low discharge within the main channel like the dammed Cudgegong. For this reason it could be expected that the Rambla de Lucainena would show similar flow characteristics to the dammed Cudgegong river: sediment concentration at the channel tributaries. Based on the model suggested by Benn and Erskine (1994) it would be expected that a river with reduced flow competence relative to its short tributaries would exhibit:

(1) A decrease in channel width just below the tributary due to rapid sedimentation, and that:

(2) Due to the lack of downstream mixing of the tributary and main channel bedload sediments there would be a concentration of the tributary bedload close to the tributary mouth.

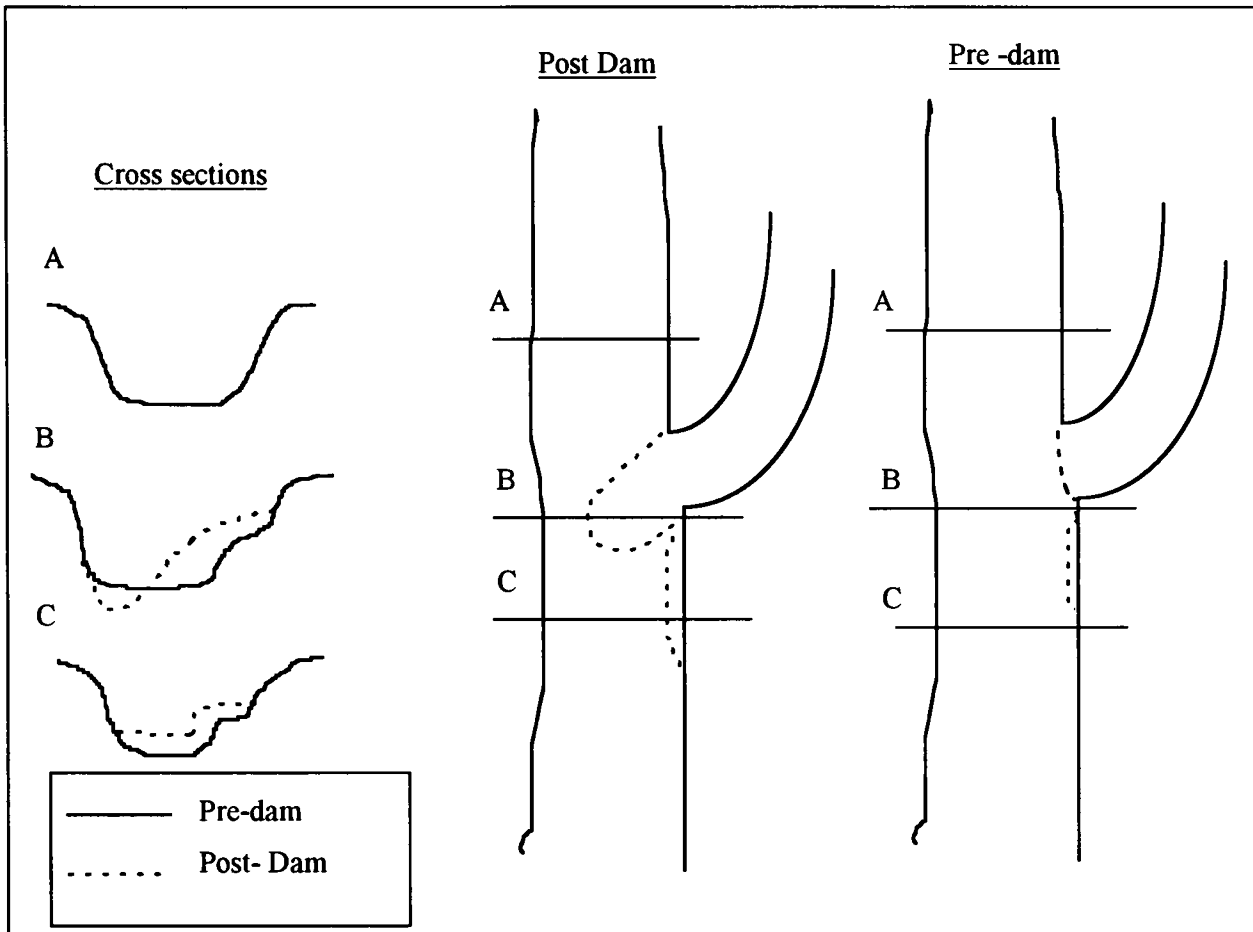


Fig. 3.1 A Model of the complex response of gravel bed streams to flow regulation. Adapted from: Benn & Erskine, 1994

To test this hypothesis in a semi-arid area three separate investigations were carried out to study each of these characteristics in the Lucainena catchment. In each of these investigations reference will be made to clast types associated with the Lucainena catchment, these will also be referred to in subsequent chapters. Table 3.1 below lists the generic terms used for each of the clast types, provides a lithological description and suggests the possible ages of source rocks for these clast types. Figure 1.5, in Chapter 1, shows the distribution of these rock types in the Lucainena catchment. It should be noted that in the upper Lucainena catchment the provenance of sandstones, marls and conglomerates has been attributed to

Tortonian sediments due to the lack of exposure of Pliocene sediments, whereas in the lower catchment distinction between these similar sediments in clast form was unreliable so a joint category of Tortonian and Pliocene sediments has been formed.

GENERIC TERMS FOR CLAST TYPES	LITHOLOGICAL DESCRIPTION	SOURCE ROCKS
fossiliferous limestone	limestones made up of reefs, oolites and algae	Messinian & Pliocene
fault zone breccia	purple sandstones, arenites and breccias	Northern Boundary Fault Zone
ironstone	iron rich dense clasts	Palaeozoic-Triassic
marble	metamorphosed limestone	Palaeozoic-Triassic
quartz		Palaeozoic-Triassic
schist	phyllites, schists, mica-schist, amphibole mica schists	Palaeozoic-Triassic
Tortonian sediments	conglomerates, grey and yellow sandstones, silty marls	Tortonian
non-fossiliferous carbonates	unfossiliferous vuggy limestone, limestone breccia, dolomite and conglomerate	Triassic & Messinian
Tortonian & Pliocene sediments	conglomerates, grey, yellow and red sandstones, silty marls, calcarenites and silts	Tortonian & Pliocene

Table. 3.1 Generic terms used for each of the clast types identified in the Lucainena catchment.

3.1.1 Channel Width

It was the aim of this investigation to prove whether the input of sediment from a tributary altered the width of the main channel close to the confluence. Eight sites were selected in different parts of the Lucainena valley in order to test the downstream width (Fig. 3.2). The widths of the main channel of the Rambla de Lucainena were measured at 10 m intervals before and after the tributary intersections. The results of this exercise are summarised in Figure 3.3.

The majority of the sites tested showed a decrease in channel width immediately following the tributary intersection. This suggests that the tributaries are inputting sediment which is not being redistributed downstream and is building up as bar deposits at the tributary confluence. This is due to the incompetence of the main channel flow which in semi-arid areas is a result of climate, which leads to low frequency high precipitation events and high rates of evaporation. A second explanation which may also be related to climate, is that the sediment deposited at the tributary junctions is the result of localised storm events in the tributary catchment which do not affect the main channel. Two sites (Fig 3.3 B & C) did not show a contraction in channel size following the tributary. In these cases it appears that the limiting factor on the channel width is the bedrock channel. The channels at each of these sites are composed of resistant bedrock just prior to the tributary intersection moving into a less resistant lithology just after it and this causes the main channel to be wider after the tributary intersection than before it.

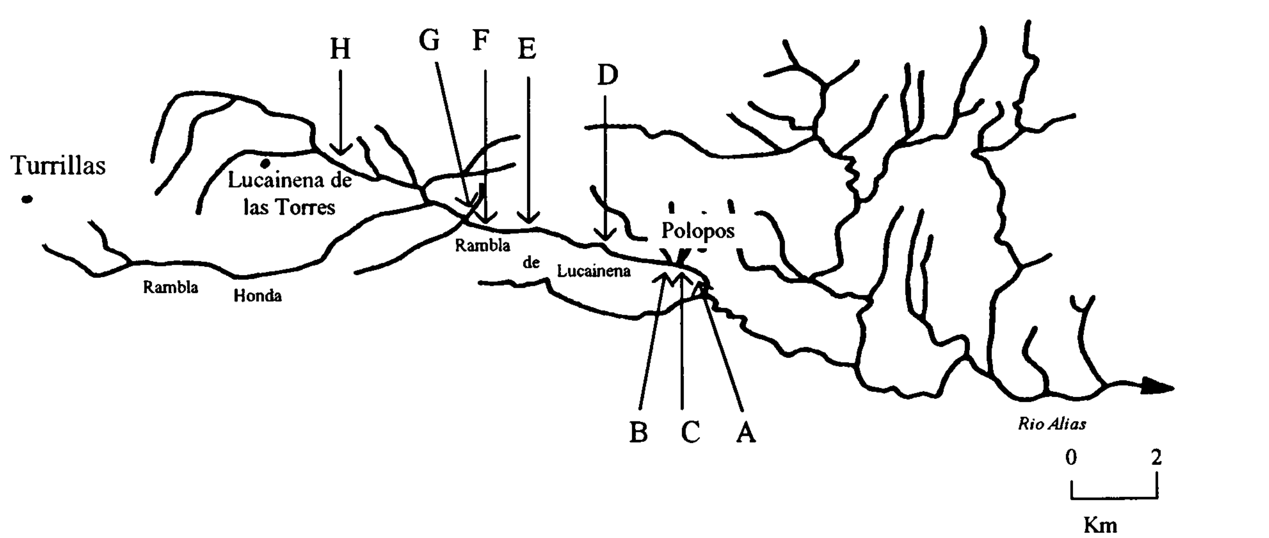


Fig. 3.2 Location of sites used to measure channel width before and after tributary junctions. The letters relate to the sites shown in Figure 3.3.

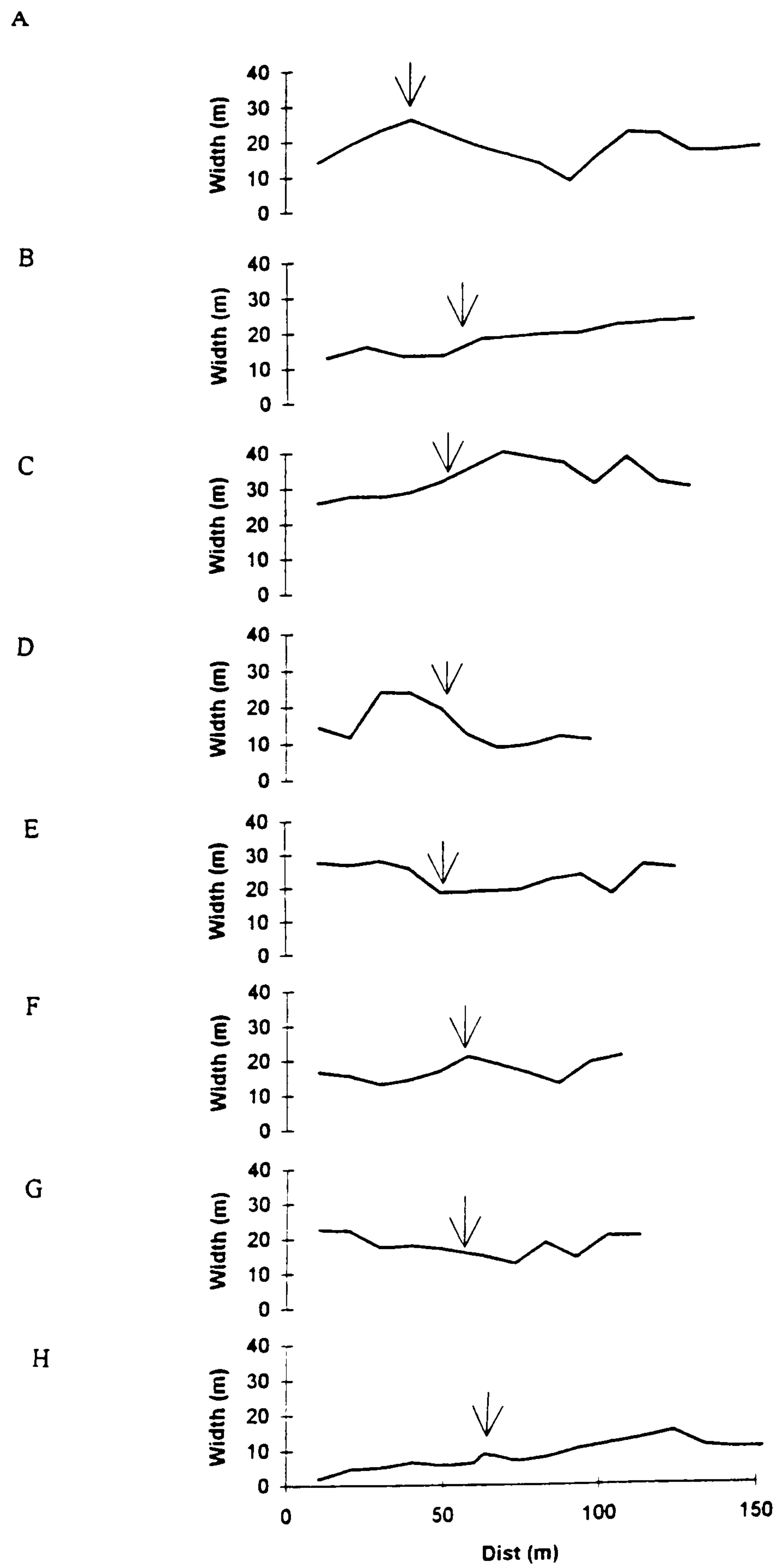


Figure 3.3 Changes in the width of the main channel after tributary junctions.
The arrows indicate the point of tributary intersection. The channels generally decrease in width immediately following the tributary intersection. For sites B & C the channel width is limited by the local geology. For site locations see Figure 3.2.

3.1.2 Concentration of Tributary Bedload

From Benn and Erskine's (1994) hypothesis it would be expected that there would be a concentration of tributary bedload at the confluence with the main channel and consequently a lack of downstream homogeneity in clast lithology. This was examined in two separate ways.

A: Investigation into bedload concentration at tributary junctions

The Baranco de Los Mortales was chosen to assess the impact of tributary bedload input into the main channel. The aim was to prove that bedload input from tributaries in semi-arid areas is not as readily mixed with the main channel bedload as that of temperate regions, due to the incompetence of flow. This leads to a high concentration of tributary bedload close to the intersection with the main channel and decreases the homogeneity of clast content. The Baranco de Los Mortales (Fig 3.4) was identified as a key site for further investigation due to the visual contrast between the tributary and main channel bedload. It was apparent from preliminary visits to this site that the input from the tributary was sometimes dominant over the input from the main channel (Fig 3.5A & B). The main channel bedload in this part of the Rambla de Lucainena consists predominantly of dark schist clasts with a small percentage of clasts of non-fossiliferous carbonates and fault zone breccia. The tributary bedload of the Baranco de Los Mortales consists of lighter non-fossiliferous carbonate clasts and clasts of fossiliferous limestones and Pliocene sediments. There is no source of Tortonian sediments from this tributary, however, when counts were made of the main channel bedload, clasts had to be categorised into Pliocene & Tortonian sediments as the upstream source of the main channel bedload also included Tortonian sediments.

To assess the bedload mixing a series of surface and trench counts were collected at regular intervals along the channel, above and below the tributary intersection. Surface counts were taken at three locations across the width of the channel , at 10 m intervals, starting 40 m above the tributary intersection and finishing 70 m below it. Trench counts were collected in the same way, but at a depth of 250 mm and spaced at 20 m intervals. The results of the clast analysis are shown in Figures 3.6 and 3.7.

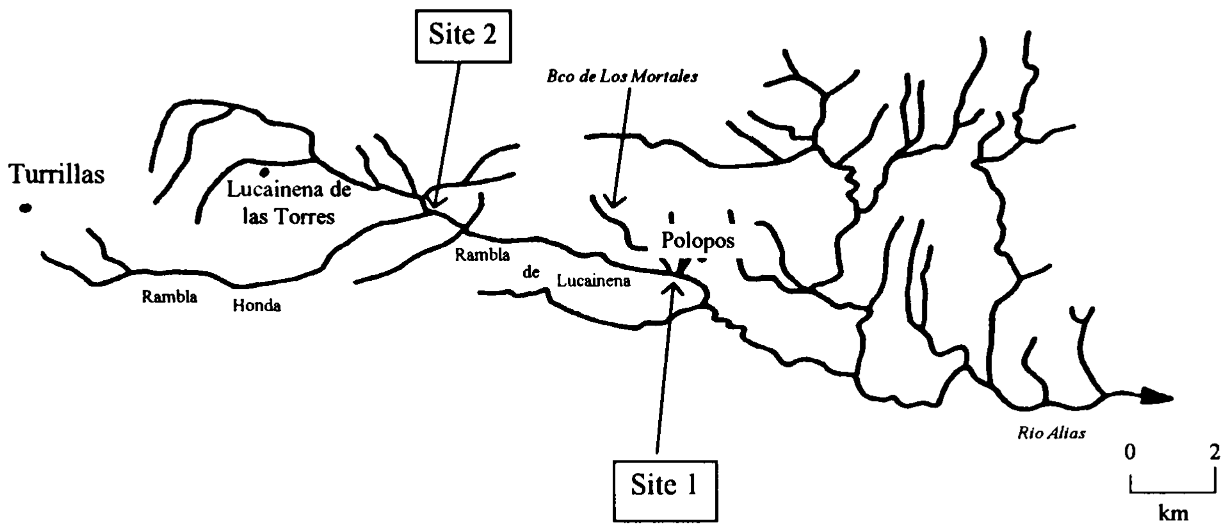


Fig. 3.4 Map showing the location of sites of further study.
Site 1 = Junction of the Baranco de Los Mortales and Site 2 = Junction of the Rambla Honda

The percentages of each of the key clast types at the different locations are shown on the diagrams and rough isopleth contours have been drawn on each to illustrate the overall trends. As can be seen from Figure 3.6A there is a high percentage of schist clasts in the main channel bedload which decreases in concentration around the tributary junction. As can be seen from the other Figures (3.6B & C) this dilution in main channel bedload is due to the input of tributary bedload close to the tributary junction. The pattern also suggests that tributary bedload is not being homogeneously mixed into the main channel bedload. Figure 3.6B and C show that there is an increase in the percentages of clasts from the tributary bedload of non-fossiliferous carbonates, fossiliferous limestones and Pliocene sediments after the tributary intersection. The concentrations are greatest close to the tributary intersection again showing a lack of homogenous mixing. The trench bedload characteristics also reflect these general patterns with a dominance in clasts from tributary bedload close to the intersection and a lack of homogenous mixing of tributary bedload with that of the main channel bedload (Fig. 3.7).

(A)

(B)

Fig. 3.5 Illustration of tributary significance- the Baranco de los Mortales (Site 1- located in Fig. 3.4). A- was taken in April 1995 showing the dominance of the main channel bedload
B-was taken in September 1995 showing a replaced input of tributary bedload into the main channel

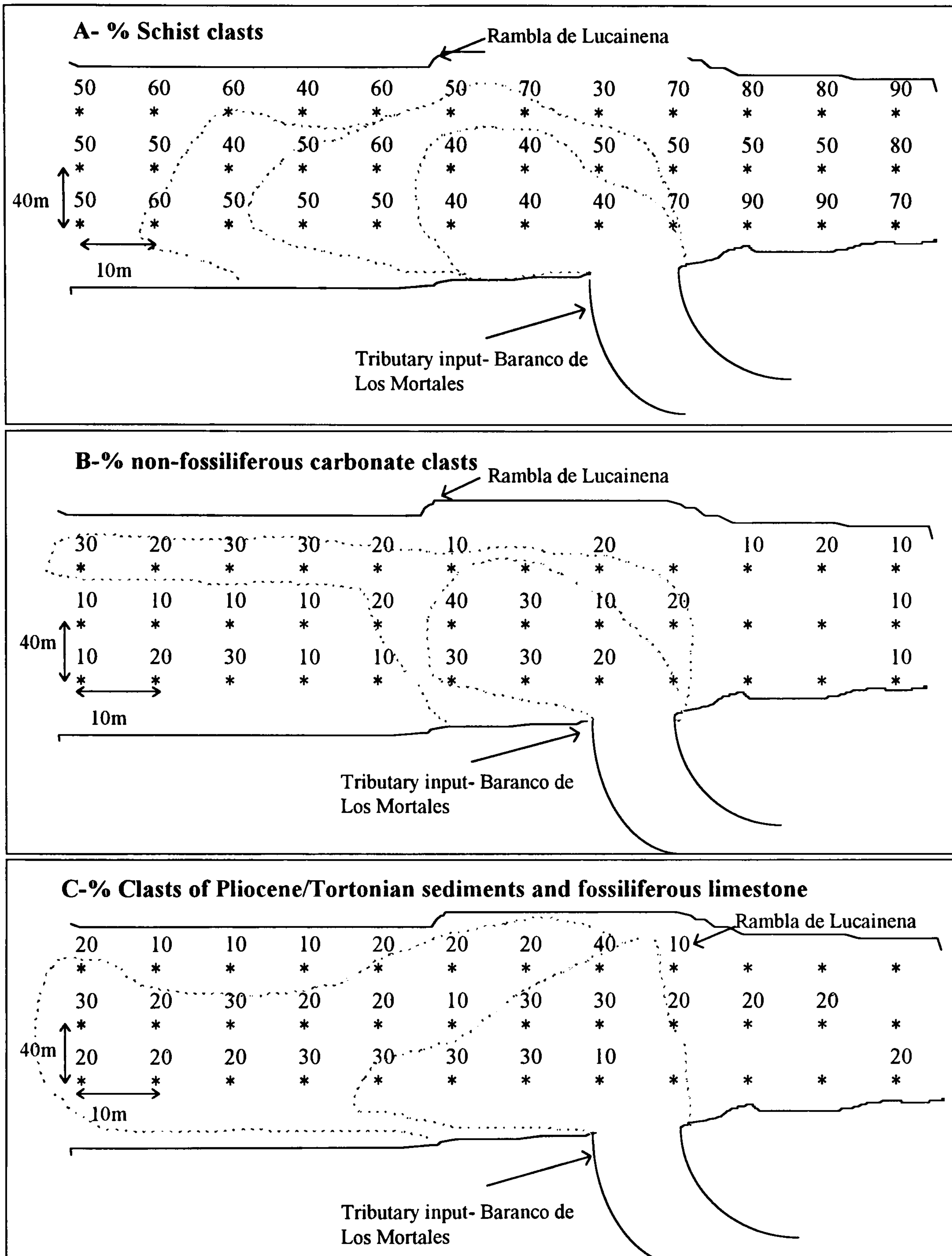


Fig. 3.6 General Isopleth Contours showing the mixing of tributary bedload downstream of the Baranco de Los Mortales tributary confluence- Surface Counts.

Note that A is showing the reduced concentration of main channel bedload and B & C are showing the increased concentration of tributary bedload. * = position of clast count.

All figures are percentage clast contributions

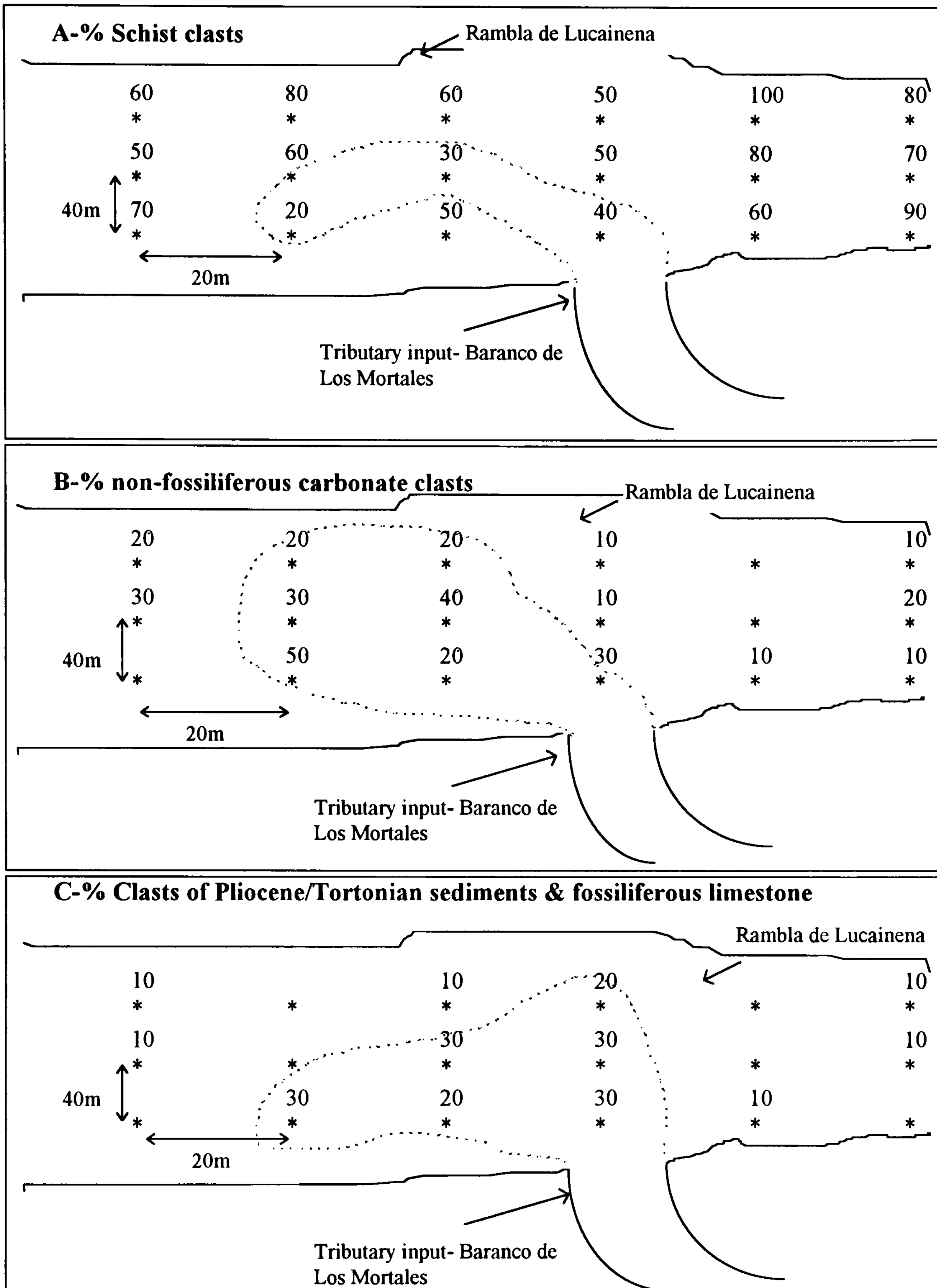


Fig. 3.7 General Isopleth Contours showing the mixing of tributary bedload downstream of tributary confluence- Trench Counts. Note that A is showing the reduced concentration of main channel bedload and B & C are showing the increased concentration of tributary bedload. * = position of clast count
All figures are percentage clast contributions

B: Investigation into homogeneity of main channel and tributary bedload mixing

The aim of this part of the study was to assess whether tributary bedload was evenly mixed into the main channel bedload at distance downstream. To determine this two sites were identified, the Baranco de Los Mortales, the subject of the previous section and the Rambla Honda, the main tributary input into the Rambla de Lucainena (Fig. 3.4). At each of the sites 100 clast counts were taken above, on and below the tributary intersection. The results of these analysis are represented in Figure 3.8 and 3.9.

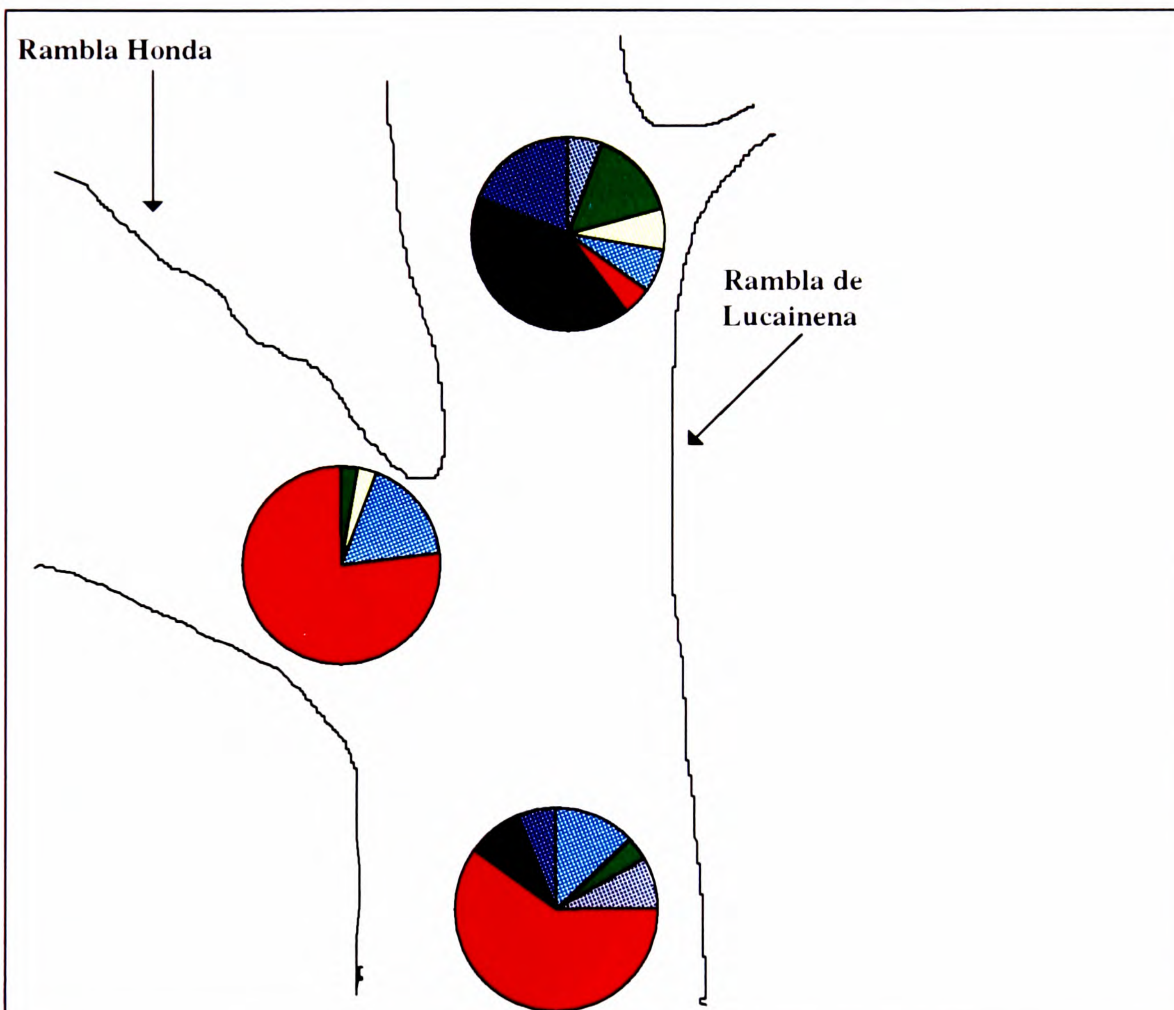
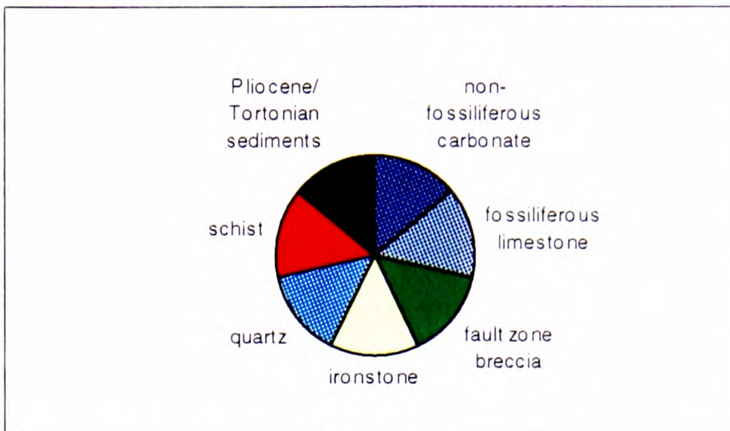


Fig 3.8 Clast assemblages above, on and below the Rambla Honda

(key on next page)



Key to Figures 3.8 & 3.9

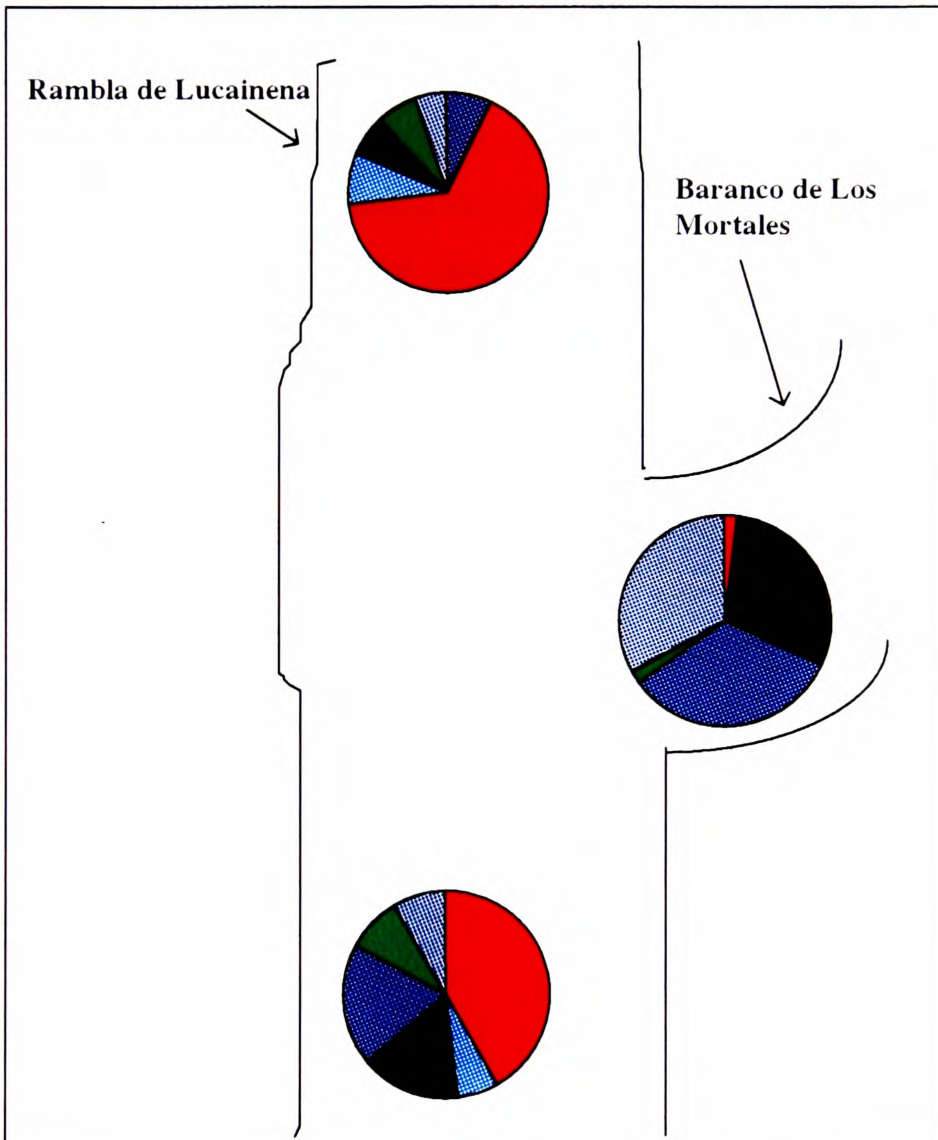


Fig 3.9 Clast assemblage above, on and below Baranco de Los Mortales

Above the Rambla Honda the bedload consists of clasts of Tortonian sediments, non-fossiliferous carbonate and fault zone breccia with only a small proportion of schist clasts (Fig. 3.8). The bedload of the Rambla Honda, on the other hand, consists predominantly of schist and quartz clasts. Below the Rambla Honda intersection the clast bedload assemblage has been altered from the Tortonian sediments and non-fossiliferous carbonates to a dominance of schist clasts from the tributary bedload.

As can be seen in Fig. 3.9 above the Baranco de Los Mortales the dominant bedload clast type was schist accounting for nearly 75% of the clasts analysed. The analysis of the bedload clasts of the Baranco de Los Mortales showed a dominance of non-fossiliferous carbonate, fossiliferous limestone and Pliocene sediments with very little schist contribution. Below the tributary intersection it can be seen that the dominance of schist clasts in the main channel bedload has been replaced by a shared clast assemblage of tributary and main channel bedload.

Both of these examples show a marked spike of tributary bedload at the channel mouth. This contrasts with temperate regions where a greater degree of bedload mixing would be expected down the main channel. Consequently it has been shown that tributaries in semi-arid areas play a significant role in the clast composition of the main channel bedload and that clasts of tributary bedload are not as homogeneously mixed downstream as one might expect from research into temperate tributaries.

3.1.3 Discussion

The result of these investigations show that:

(1) There is an overall decrease in channel width just after each tributary junction due to a combination of waning flow and rapid sedimentation.

(2) There is an increase in the concentration of tributary bedload close to tributary junctions and a lack of downstream homogenous mixing.

These conclusions fit the hypothesis laid out by Benn and Erskine (1994) about flow characteristics when the main channel is reduced in transport capacity relative to its tributaries, showing that flow in semi-arid areas is very different to flow in temperate regions and is contemporaneous with channel behaviour due to regulated flow. The significance of these conclusions will be discussed in Section 3.3 with reference to its implications on determining the Quaternary drainage history.

3.2 EROSION DATA

The erosion data discussed in this section were collected from 3 sites within the Lucainena catchment. Each of these sites was chosen to represent one of the key lithologies of the Lucainena catchment: Tortonian sediments, weathered schist and regolith & Messinian sediments reworked from Triassic rocks (Table 3.2). These lithologies are found within the Quaternary river gravels of the Rambla de Lucainena. It is therefore the aim of this section to determine the relative erodibility of these deposits from the data collected at each of these sites and to assess their potential contribution to the Quaternary sediments.

Site Lithologies	Bedrock at site	Average depth of weathered Regolith
Tortonian Sediments	bedded yellow/grey marls, fine sandstones and silts	200 mm (fairly uniform across section)
Schist Deposits	grey phyllites, schists and mica schists	200 mm (fairly uniform across section)
Messinian Deposits	dark grey dolomitic limestone conglomerate with cream fine grained sandy matrix	150 mm (varied considerably across section)

Table 3.2 Lithological description of the sites of contemporary erosion investigation

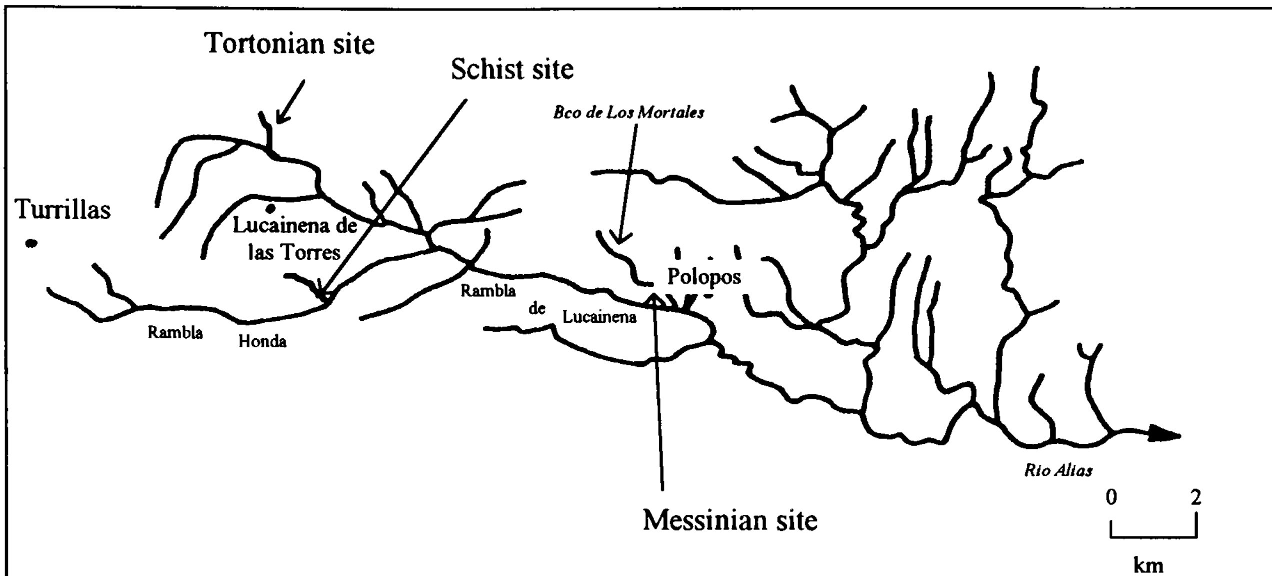


Fig. 3.10 Map showing location of contemporary erosion data collection sites.

3.2.1 Tortonian Sediments

The site of data collection for the Tortonian sediments was a small tributary feeding into the main channel of the Rambla de Lucainena (Fig. 3.10). It is situated in the upper reaches of the Lucainena catchment and drains an area of 0.45 km^2. Two erosion grids and two erosion profiles on opposing slopes, a sediment trap at the mouth of the catchment and three channel profiling sites to monitor the rate of channel movement were installed (for full site details -see Table 2.1). All of the erosion pins were hammered into *in situ* weathered regolith consisting of marls and fine sandstones on poorly vegetated slopes (20% cover).

Erosion rates

The average erosion for this site was 0.17 mm $month^{-1}$ (Table. 3.3). The maximum erosion of 31 mm and maximum accretion of 23 mm were recorded on the east facing slope (Table. 3.3). Overall the rate of accretion exceeded the rate of erosion on each of the grids and profiles, showing that during the period of study this site received more sediment than was eroded from it. Sediment movement on the grids appears to be at a maximum between the months of January and September (Fig. 3.11). Table 3.3 shows that the north-west facing slopes eroded less over the period of study than the east facing slopes. As both the slopes were similar in terms of slope angle and vegetation cover one explanation for the difference is the amount of sunlight received on both of the slopes. The north-west facing slopes receive less sunlight than the east facing slopes, therefore, the slopes would remain wet with dew for longer. This suggests that dry Tortonian sediment is more prone to displacement than 'dew' damp sediment due to the cohesion properties of water.

Deposition rates

As shown in Figure. 3.12, two yields of sediment were recorded during the period of study. The largest of these was obtained between September and January where 68 kg of sediment was yielded. A smaller yield of 5 kg was recorded between April 95 and September 95. Overall the site yielded 73.5 kg.

	Grid		**Profile**		**Whole site**
	E facing	**NW Facing**	**E Facing**	**NW Facing**	
Gross Average					
mm month^{-1}	0.6	0.6	0.2	0.2	0.4
mm year^{-1}	8.2	8.4	2.9	2.3	5.5
Max. accretion (mm)	16	8	23.0	15	23.0
Max. erosion (mm)	-23.0	-23.0	-31.0	-15.0	-31
Standard Deviation (mm)	8.0	8.4	7.80	7.40	
Average accretion					
mm year^{-1}	11.5	8.4	7.9	4.00	8.0
mm month^{-1}	0.88	0.65	0.61	0.31	0.6
Average erosion					
mm year	3	0	4	2.00	2.25
mm month	0.23	0.00	0.31	0.15	0.17
mm^3 month^{-1} km^{-2}	897436	0			
mm^3 year^{-1} km^{-2}	11666667	0			
Kg year^{-1} km^{-2}	17	0			
Deposition data					
Kg year^{-2}					73.5
Kg year^{-1} km^{-2}					163.3

Table 3.3 Summary table of erosion & deposition data for the Tortonian site. In the first 3 rows the accretion values are given as positive values and the erosion values are given as negative values.

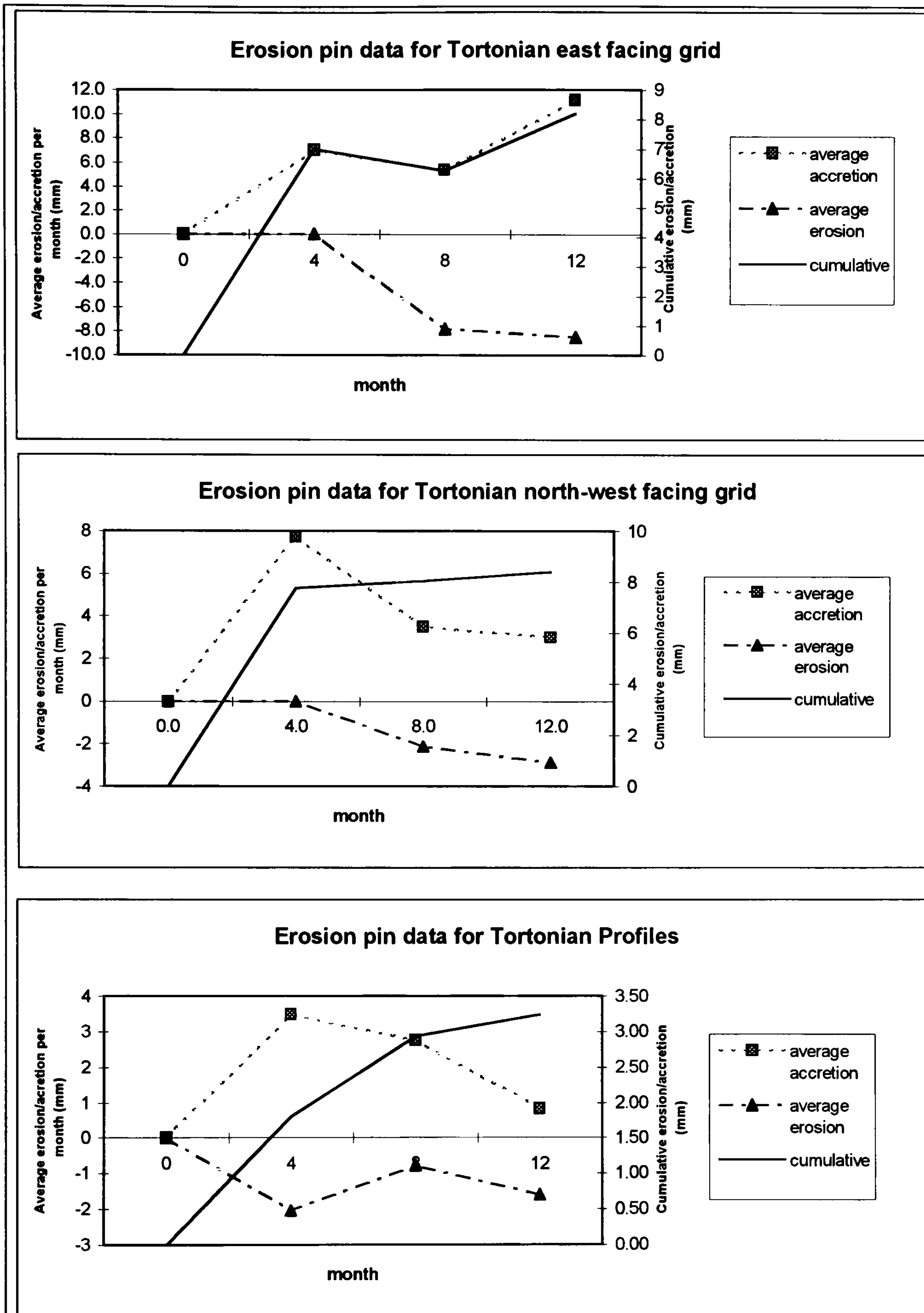


Fig. 3.11 - Tortonian Erosion Data.
Month 0= September 1994 and Month 12= September 1995

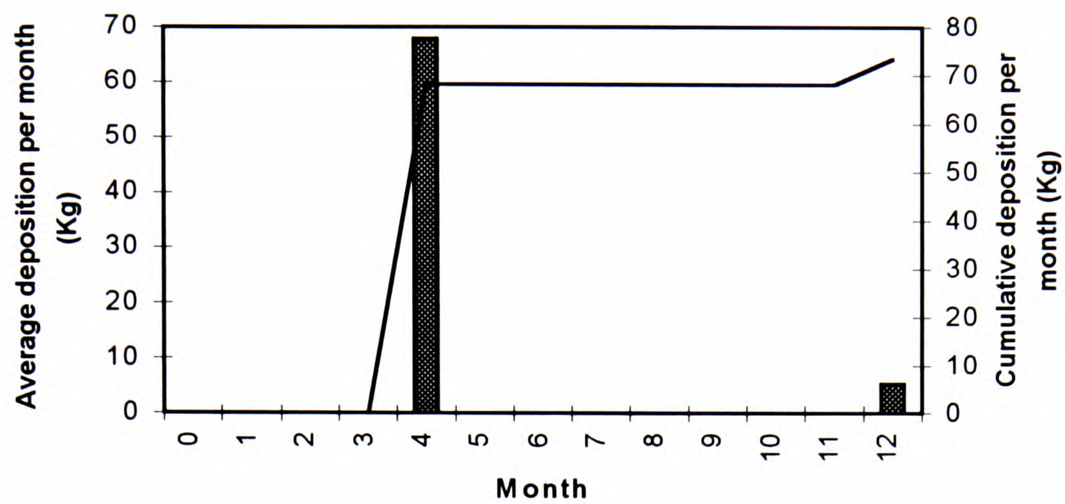


Fig. 3.12 Sediment deposition for the Tortonian catchment.
Month 0 = September, 1994 and Month 12= September, 1995

Micro-scale maps

Data were also collected to record the rate of channel shifting of the tributary channel. This was done by measuring the channel profile at three locations up the tributary channel (Fig. 3.13 & 3.14). The greatest displacement was recorded at the site nearest the channel confluence (Fig. 3.14A) where the channel bank shifted 500 mm to the west in just 4 months giving an erosion rate of 1500 mm year^{-1}.

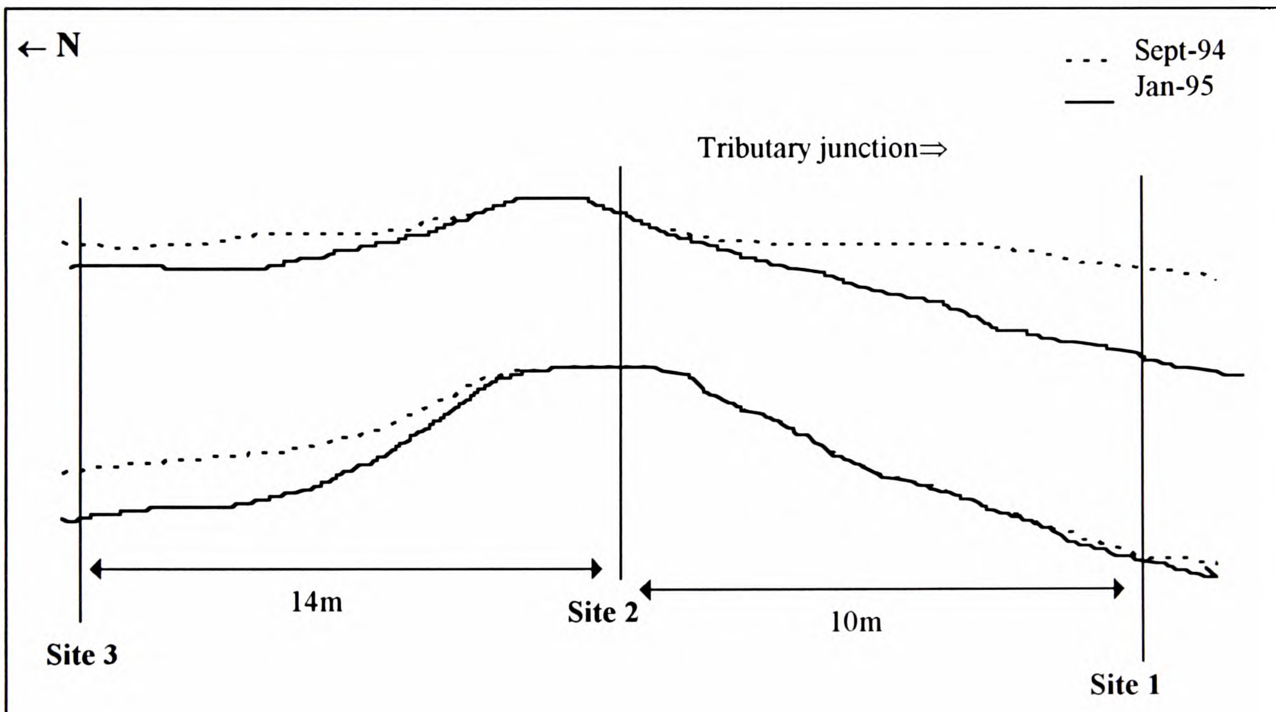


Fig. 3.13 Sketch plan of tributary section showing sites of channel cross sections illustrated in Figure 3.14 and the movement of channel banks over time.

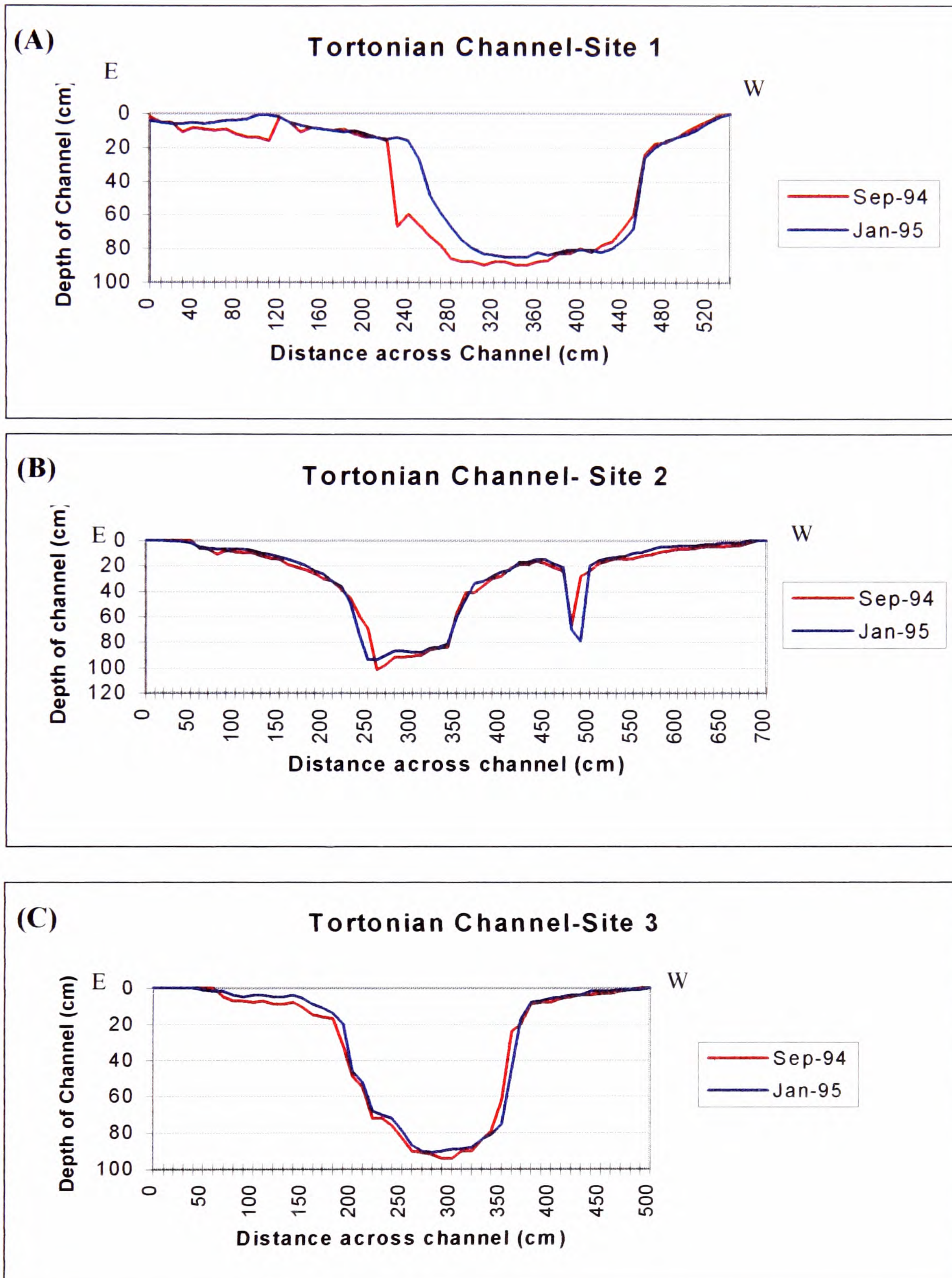


Fig. 3.14 Profiles across Tortonian Channel to show channel shifting
The location of the channel cross-sections for sites 1 to 3 is shown in Figure 3.13

Comparison of Erosion & Deposition Rates

The average erosion rates listed in Table 3.3 were used to calculate the potential volume of sediment yield for each site. This was done by converting the volume of sediment into a weight using the specific gravity of the sediment and multiplying this weight by the total area of the site. The potential yield for the Tortonian site calculated by this method was 17 kg $year^{-1}$ km^{-2} (Table. 3.3). The actual volume of sediment deposited over the year long study period was 163.3 kg km^{-2}, far greater than the predicted volume of sediment. There are several possible explanations for this difference in volume:

(1) The majority of sediment collecting in the check dams is the result of eroding gullies and not from sheetwash as monitored by the erosion grids (Fig. 3.14).

(2) The majority of the sediment being deposited within the checkdam is derived from sediment storage on the lower slopes of the catchment (Fig. 3.15). This sediment has been eroded over a larger period of time than that of this study and is infrequently cleared from the catchment. Therefore, stored sediment could represent years of erosion and accumulation, whereas the predicted volume of sediment was only calculated on the basis of a year's erosion.

(3) The recurrence interval of severe storm events in this region is likely to be much greater than the period of study. Higher erosion rates would have been expected if there had been a major storm event, but during the year of data collection there was none. Therefore, to calculate a more representative erosion rate it would be necessary to increase the study period to include a major storm event. This indicates that the actual sediment yield does include stored sediments as suggested in explanation (2).

(4) The slope angles of the erosion grid sites may not be representative of the whole catchment suggesting lower erosion rates than those likely for the rest of the catchment. If the slopes in the rest of the catchment are steeper than those selected for the erosion grids then a higher erosion rate could be expected. However, the sites used for the collection of data were chosen to be representative of most of the slopes in the catchment.

(5) The method used to estimate the volume of sediment yielded for the site required an estimation of the density of the sediment. The density of dry silt was used for this purpose which may not have been wholly representative as the site consisted of a combination of sediments and would not have been dry at all times.

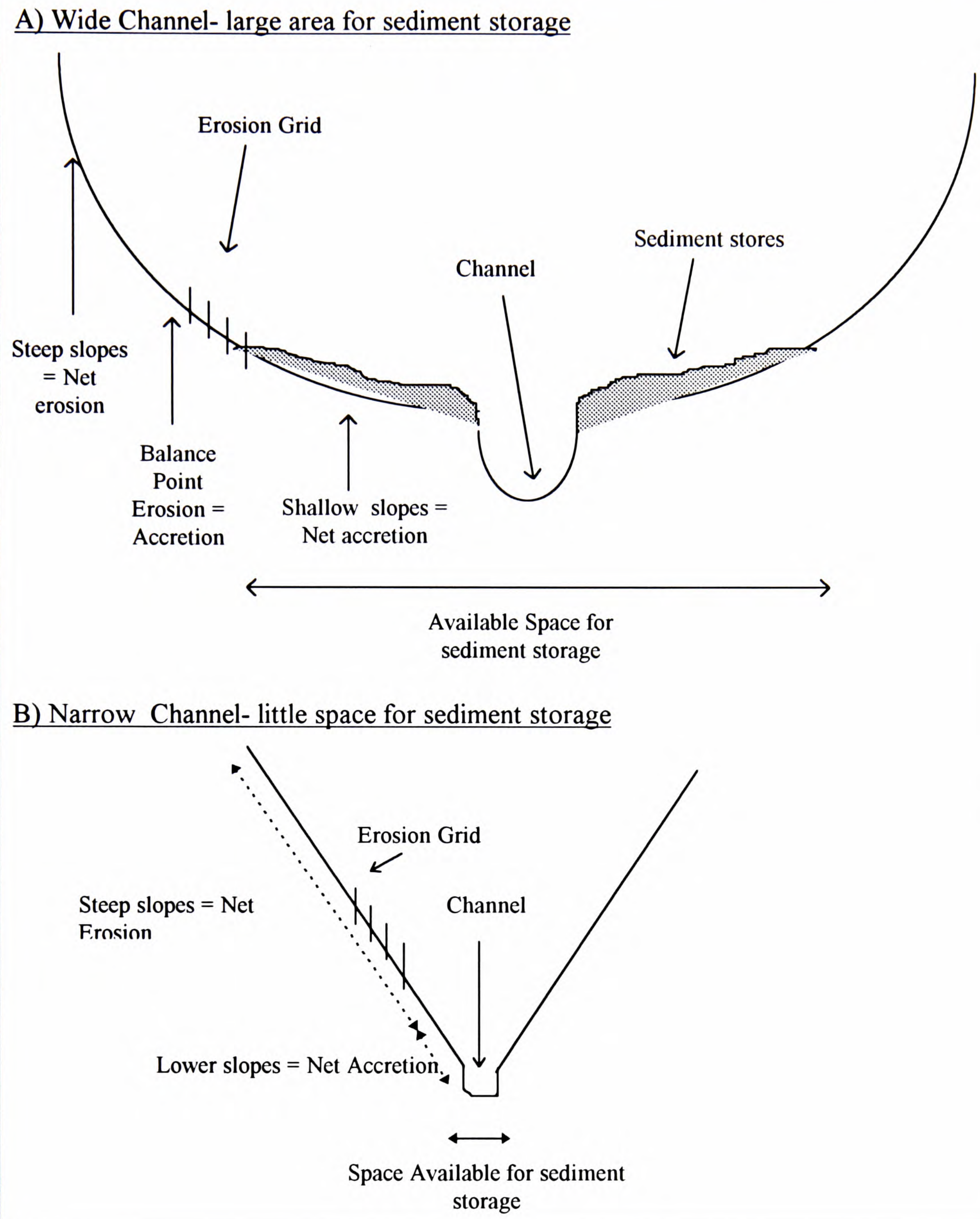


Fig. 3.15 Channel shapes and their ability to store sediment

The difference in predicted and actual yield is best explained by reasons 1 to 3, with the most influential factor being explanation 2. This is because this catchment has a wide cross section enabling large amounts of storage on its lower slopes. This means that sediment which has eroded over a large period of time is built up and stored within the channel until a larger storm event washes out this stored sediment. It is therefore reasonable that the large volume of sediment which accumulated within the checkdam was due to the movement of stored material, which had eroded at these low erosion rates, but over a significantly longer time than the period of study.

3.2.2 Schist deposits

The site identified for the analysis of the weathered schist deposits was a small tributary feeding into the Rambla Honda (Fig. 3.10). The Rambla Honda is a major tributary of the Rambla de Lucainena. The schist tributary was heavily vegetated (70% coverage) and drained an area of 0.6 km^2. The site consisted of two erosion grids and two erosion profiles on opposing slopes, a sediment trap at the tributary confluence and a gully section to assess the rate of tributary capture (for full site details- see Table 2.1). All of the erosion pins were hammered into *in situ* weathered regolith.

Erosion Rates

The average erosion rate for the site was 0.98 mm $month^{-1}$ (Table. 3.4). The maximum erosion was 57 mm on the south-east facing slope and the maximum accretion was 29 mm on the opposing north facing slope. Overall the site showed a net accretion of sediment around the pins, however, it can be seen from Figure 3.16 that the grid on the north facing slope and the profile showed net erosion over the period of study and that the erosion was greatest between the months of September and January. This discrepancy over erosion on the north facing slopes and accretion on the south is not immediately apparent, but could reflect subtle variations in the regolith characteristics.

Deposition Rates

During the period of study no sediment collected within the sediment trap despite the high erosion rates of this site.

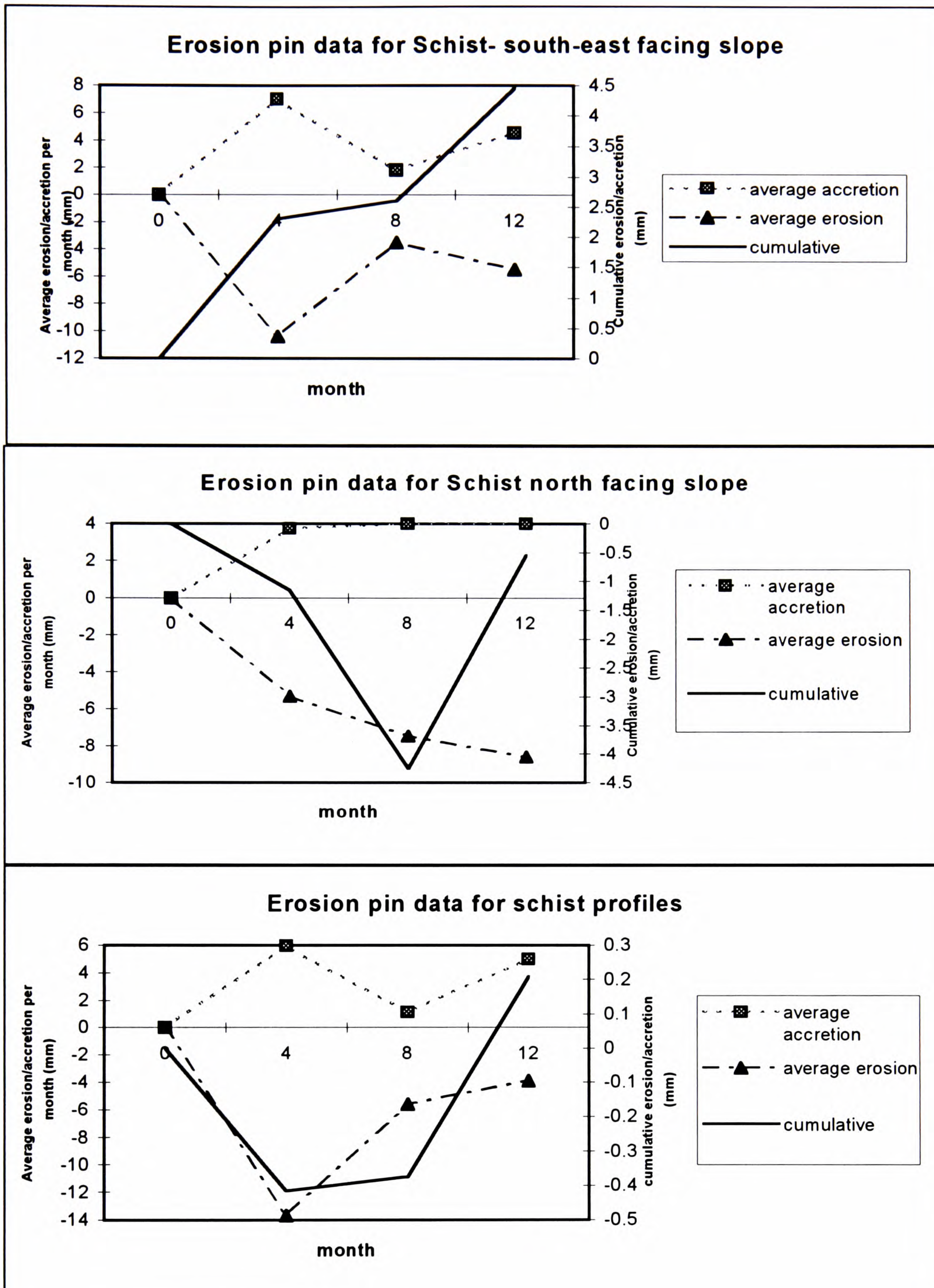


Fig. 3.16 Schist Erosion Data.
Month 0= September 1994 and Month 12= September 1995.

	Grid		Profile		Whole site
	SE Facing	N Facing	SE Facing	N Facing	
Gross Average erosion					
mm month^{-1}	-0.37	0.05	-0.04	0.25	0.02
mm year^{-1}	-4.5	0.6	-0.4	3.4	0.2
Max. accretion (mm)	15	29	10	13	23
Max. erosion (mm)	-23	-30	-57	-20	-31
Standard Deviation (mm)	11.4	12.5	17.6	7.2	
Average accretion					
mm year^{-1}	9.9	11.9	7.9	3.5	8.3
mm month^{-1}	0.76	0.92	0.61	0.27	0.64
Average erosion					
mm year^{-1}	14.5	10	19.3	7.30	12.78
mm month^{-1}	1.12	0.77	1.48	0.56	0.98
mm^3 month^{-1} km^{-2}	3253205	2243590			
mm^3 year^{-1} km^{-2}	42291667	29166667			
Kg year $^{-1}$ km^{-2}	112	77			
Deposition data					
kg year^{-1}					0
kg km^{-2}					0

Table 3.4 Summary table of erosion & deposition data for the schist site. In the first 3 rows the accretion values are given as positive values and the erosion values are given as negative values.

Micro-scale Maps

At this site a small headcutting gully feeding into the tributary was selected as the subject of further study. The aim was to deduce the rate of headcutting. Erosion pins were set up in a line behind the gully and the distances from the pins to the gully were measured at regular intervals. The erosion around the pins was also measured. Figure 3.17 shows a plan view of the head of the gully and its position at the intervals measured. The average rate of headcutting was 7.2 mm month^{-1}. The land was eroding vertically around the pins at a rate of 0.6 mm month^{-1} These figures show that erosion is occurring at a greater rate in the gullies than on the slopes of the schist catchment. The greatest headcut occurred between the months of September and January.

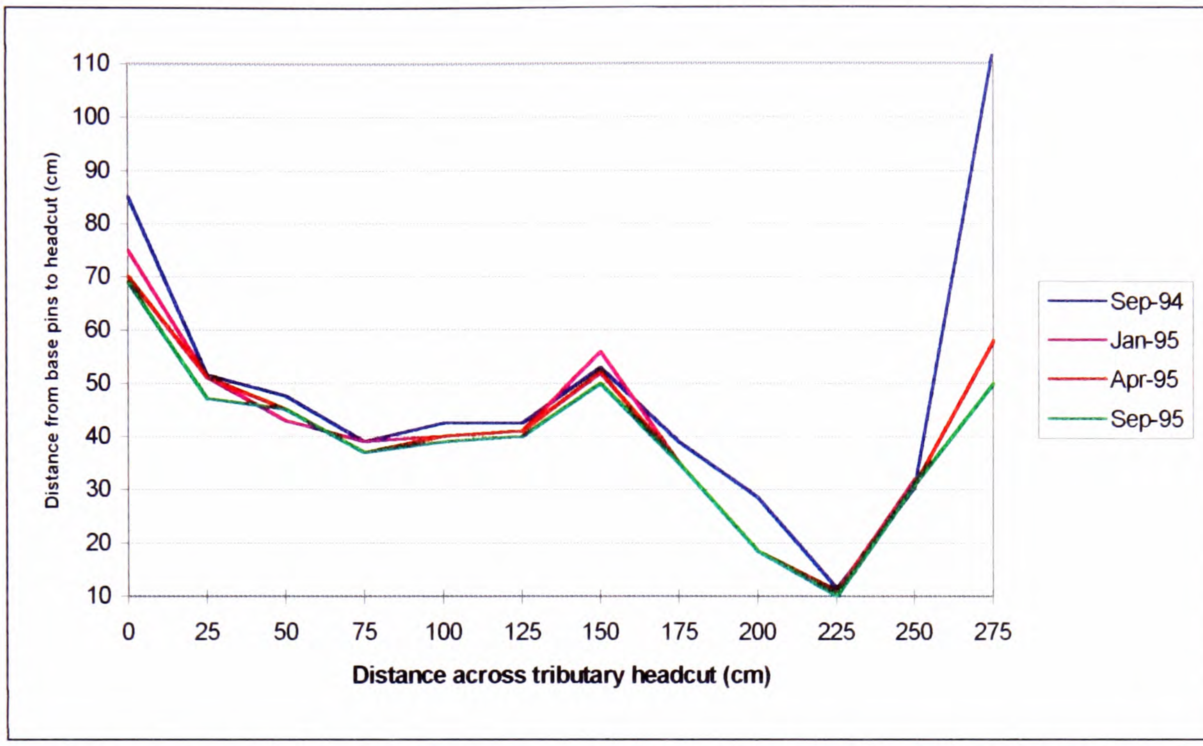


Fig. 3.17 Rate of tributary capture in the schist catchment.
This is a plan section.

Comparison of Erosion & Deposition rates

The predicted amount of sediment to be yielded from this site based on the erosion rates is 112 kg year^{-1} km^{-2}, however, this site yielded no sediment over the period of study. There are several explanations for this lack of yield:

(1) There was no significant storm event during the period of study.

(2) The eroded sediment is being stored on the lower slopes or higher up in the tributary (Fig 3.15B).

(3) The highly vegetated slopes are trapping sediment and slowing the movement of sediment down the slopes to the main channel.

(4) The slopes on which the grids and profiles were installed are eroding faster than the rest of the site.

The first two explanations are likely to be the most significant. This is because the channel is quite narrow enabling minimal storage of sediment on its slopes. Therefore, if there had been some rainfall it would have been expected that the site would yield a moderate amount of sediment because there is no where to hold the sediment in the catchment (Fig 3.15B). The presence of rainfall in the Tortonian catchment and lack of a substantial rainfall event in the schist catchment demonstrates the extremely localised climate experienced in semi-arid areas.

3.2.3 Messinian Deposits

The analysis of the weathered Messinian deposits was carried out in the lower reaches of the Rambla de Lucainena on a tributary section inputting directly into it (Fig. 3.10). The site is the Baranco de Los Mortales whose drainage area is 3.78 km^2. The site comprised of boulder beds of reworked Triassic limestones and dolomites with minimal vegetation (10% cover). Due to the hard nature of these deposits the site was set up with only two grids on opposing slopes hammered into the *in situ* weathered regolith and a checkdam situated at the tributary confluence (For full site details- see Table 2.1).

Erosion rates

The average erosion for the site was 0.04 mm $month^{-1}$ (Table 3.5.), although overall the site received more sediment than was removed from it. Table 3.5 and Figure 3.18 show that the west facing slope eroded to a maximum of 15 mm and the east facing slope accreted to a maximum of 54 mm, over the period of study. The eroding and accreting slopes contrast with Site 1, and could reflect several variables, including: (1) increasing water flow on the shadier west slopes; or (2) alternatively some facies variation in the weathered regolith. In practice the data is insufficient to resolve the role played by aspect and micro-climate. Again the greatest amount of erosion occurred between the months of September and January (Fig. 3.18).

Deposition Rates

During the period of study two yields were collected in the checkdam totalling 680.5 kg. The first and largest yield occurred between January and April and weighed 669 kg, with a second smaller yield between April and September of 11.5 kg (Fig. 3.19).

	Grid		Whole site
	E	W	
Gross Average			
mm $month^{-1}$	0.375	-0.19	0.09
mm $year^{-1}$	4.5	-2.3	1.11
Max. accretion (mm)	54	10	54
Max. Erosion (mm)	-7	-15	-15
Standard Deviation (mm)	13.0	7.0	
Average accretion			
mm $year^{-1}$	1	0.9	0.96
mm $month^{-1}$	0.08	0.07	0.07
Average erosion			
mm $year^{-1}$	-0.29	-0.63	-0.46
mm $month^{-1}$	-0.02	-0.05	-0.04
mm^3 $month^{-1}$ km^{-2}	-102386	-6359.38	
mm^3 km^{-2}	-1331019	-82672	
kg $year^{-1}$ km^{-2}	0.31	0.67	
Deposition data			
kg $year^{-1}$			680.5
kg km^{-2}			180.0

Table 3.5 Summary table of erosion & deposition data for the site.
In the first 3 rows the accretion values are given as positive values and the erosion values are given as negative values.

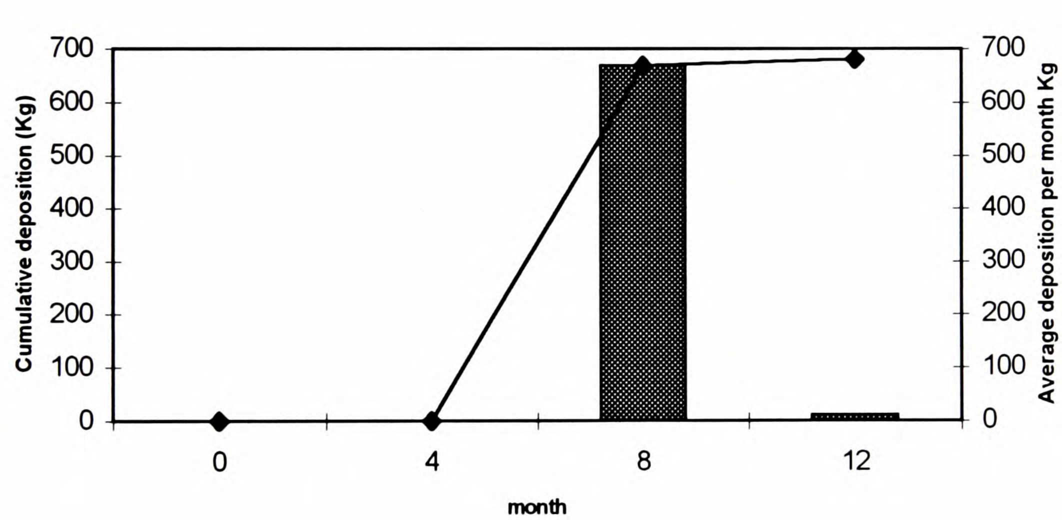


Fig. 3.19 Messinian Sediment deposition.
Month 0 = September, 1994 and Month 12= September, 1995

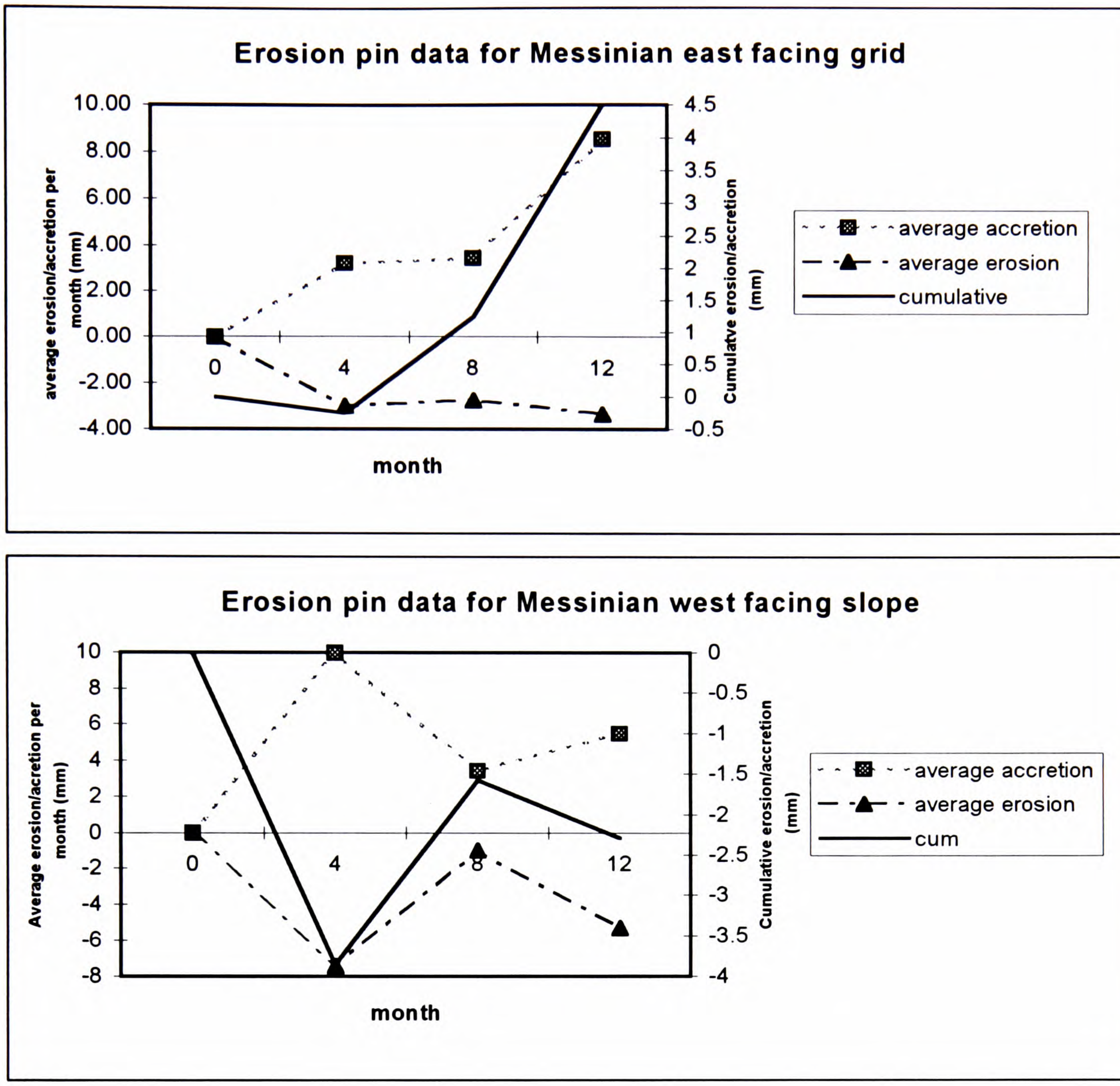


Fig. 3.18 Messinian Erosion Data.
Month 0 = September 94 and Month 12 = September 95

Comparison of Erosion & Deposition Rates

The maximum predicted yield for this site based on the erosion rates was 0.67 kg $year^{-1}$ km^{-2} which gives a total yield of 2.5 kg, for this 3.78 km^2 , site in the year study. The actual yield for this site was far greater, 680.5 kg, there are several explanations for this significant discrepancy:

(1) The majority of the deposited sediment is coming from the stores of sediment on the lower slopes within the catchment adjacent to the main channel (Fig. 3.15A).

(2) These stores represent the product of erosion over a large period of time, significantly larger than the period of study.

(3) The slopes in which the erosion grids were set up may not be eroding as fast as other parts of the site.

(4) Some of the sediment accumulated may be the result of eroding gullies, however, few gullies are apparent at this site.

(5) A proportion of the sediments within the checkdam are Pliocene limestone and sandstone sediment sourced from the head of the tributary. This could be more erodible, however, visual inspection suggests that they are of similar geological competence.

The differences between the erosion and deposition amounts at this site are most readily explained by 1, 2 and 5. This is because the channel has a reasonably wide cross-section suitable for storage, meaning that eroded sediment is stored for a significantly large period before it is flushed out to the main channel. The input of Pliocene sediments may slightly increase the volume of deposited material but due to the similar lithological hardness and fracture density, it would be expected that the erosion rates would be similar.

3.2.4 Discussion

The schist regolith is eroding the fastest (0.98 mm month^{-1}), with the Tortonian eroding the second fastest (0.17 mm month^{-1}) and the Messinian showing the slowest rates of erosion (0.04 mm month^{-1}). The erodable nature of the schist could be explained by it containing more readily weathered platy mica minerals than either the Tortonian or Messinian sediments.

The deposition data shows the reverse of the erosion data, with the maximum input of sediment from the Messinian catchment, then the Tortonian and lastly none over the period of study from the schist. Because the erosion rates for the Messinian and Tortonian sediments are low, but the sediment yield is high it is likely that these sites are storing large volumes of sediment which have accumulated over a large period of time. The schist site on the other hand eroded the fastest over the period of study but yielded no sediment. This simply reflects the absence of a storm event sufficient to cause stream flow in the schist catchment. The steep sided nature of this catchment, however, is not suitable for sediment storage and had an event occurred it would presumably have yielded only a little amount of sediment more balanced with the rate of catchment erosion.

At each of the sites an element of aspect control was recorded with different rates of erosion occurring on opposing slopes. This suggests that slope aspect and not just lithology are dominant in the control of erosion from slopes. Interestingly it appears that aspect has differing impacts on different lithologies, the schist deposits showed greater erosion on the wetter slopes and the Tortonian greater erosion on the drier. However, it is impossible to make any substantive conclusions about the influence of slope aspect due to the limits of the data, but this could be of significant interest as a matter of further study.

Unfortunately there were no major storm events during the period of study, therefore, the erosion pins are mainly recording sediment movement associated with rainsplash and normal slope processes rather than major transportation associated with large scale flooding events. However, this was not a limitation to the study as it is this type of small scale movement which is characteristic of the erosional processes occurring for the majority of the time in semi-arid areas.

In general the sites analysed show more accretion than erosion. This could be due to several factors:

(1) The interference of the pins with the natural slope processes. In some instances a build up of sediment was observed around the pins where rain splash had caused sediment to stick to them. This is a limitation of most forms of erosion measurement and therefore was considered to be of minimal impact to this study.

(2) The position of the grids on the slope. Due to the nature of slope processes the upper steeper slopes will be eroding the most sediment and the lower shallower slopes accumulating it (Fig 3.15). This means that if the grids are positioned on the lower slopes then they will be accumulating more sediment than is being removed.

(3) Sediment may be being eroded but not being transported very far due to the infrequency of storm events. During the period of study no major storm events sufficient to move large quantities of sediment were recorded, therefore, any eroded sediment will accumulate on the slopes.

All of the sites show an increase in the amount of sediment movement during the months of September and January, this could suggest higher rainfall levels experienced during these months or be due to the initial ground disruption associated with hammering the pins in.

3.3 CONCLUSIONS & IMPLICATIONS FOR QUATERNARY DRAINAGE EVOLUTION

3.3.1 Conclusions

Overall, this preliminary analysis has revealed a number of interesting conclusions:

(1) There is a decrease in the main channel width just below each tributary junction. This is because the main channel flow is incompetent and bedload which is flushed out of the tributary channel is not readily removed from the mouth of the tributary. This causes a build up of sediment just below the tributary mouth and effectively reduces the width of the main channel.

(2) There is a lack of homogeneous bedload mixing downstream of tributaries in semi-arid rivers. This is because the relative discharge strength of the main flow is low relative to its tributaries, leading to a concentration of tributary bedload close to the junction with the main channel.

(3) The lithologies within the catchment erode at different rates. Out of the lithologies investigated the schist eroded the fastest, then the Tortonian and lastly the Messinian. This contrasts with what we would expect to occur as schist is generally more resilient to erosion than the sandstones and marls of the Tortonian sediments, a situation which is reflected in their channel morphology, with schists having narrow steep channels and Tortonian sediments exhibiting wider gentler sloped channels. The most likely reasons for higher erosion rates in the schist rather than the expected Tortonian sediments are: (A) that the schist is made up of more readily weathered platy mica minerals; and (B) that the Tortonian sediments exhibit

a protective crust which forms on the surface of the sediments giving an increased resistance to erosion.

(4) Channel morphology was also found to be an important factor concerning the input of sediment into the fluvial system. It was found that the wider channels of the Tortonian and Messinian sites had a greater capacity for storage than narrower channels such as those of the schist site. This may explain the imbalance between erosion rate and sediment transport at these sites. The Tortonian and Messinian sites exhibited the lower erosion rates but yielded large volumes of sediment, this was because the sediment yield was related to stored sediment eroded over a number of years. The schist site on the other hand exhibited higher erosion rates but showed no yield, this can be explained by the lack of storage at this site, as it would take a number of years even at these higher erosion rates to yield a significant amount of sediment to be washed into the checkdam.

3.3.2 Implications for Drainage Reconstruction

Each of the above conclusions could be the focus of further study but have been investigated here to aid in the correlation of Quaternary terraces as discussed in the next chapter. The implications of these conclusions which must be considered within the Quaternary drainage reconstruction are discussed below:

(1) The build up of sediment at the mouths of tributaries could alter the gradient of terrace profiles. This influx of tributary bedload is not removed and carried further downstream as with temperate rivers and this means that the channel gradient at the tributary confluence could be elevated. This could lead to a stepped terrace profile as opposed to a smooth terrace profile associated with temperate regions (Fig. 3.20). This may be of importance when correlating terrace fragments on a height distance diagram.

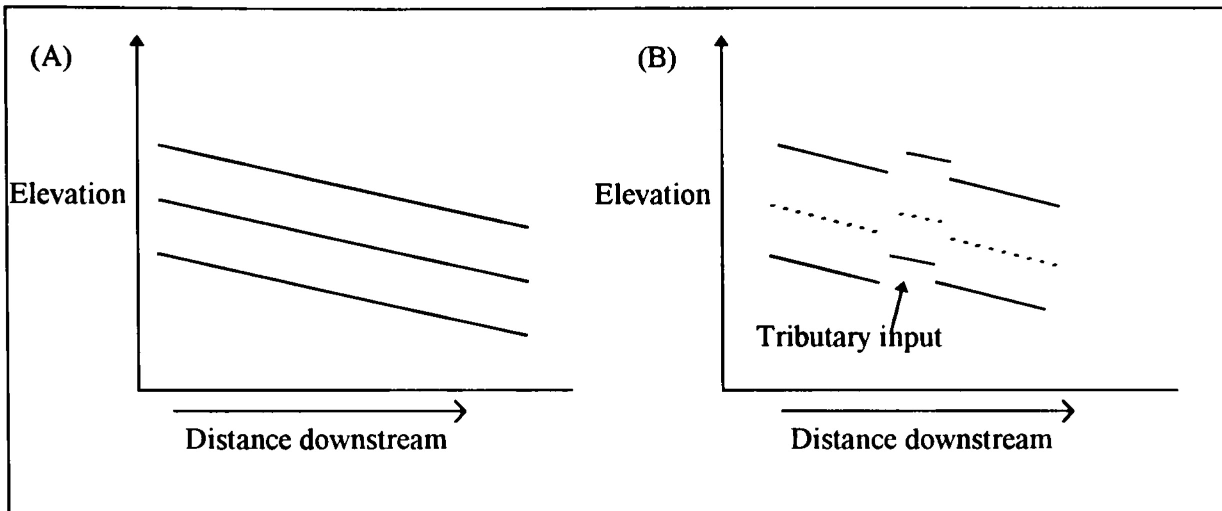


Fig. 3.20 Terrace graphs illustrating stepped terraces as a result of tributary input raising the elevation of the main channel.
(A) shows the smooth terrace graph of a temperate river and (B) the expected stepped terraces of a semi-arid river with significant tributary inputs

(2) The best sequences of terraces will be associated with tributary junctions due to the large volumes of sediment input at these points. In semi-arid regions this sediment will not be integrated into the main channel sediment and is stored close to the tributary confluence. Any alteration in base level may result in this sediment forming a terrace bench. It is also likely that there will be a decrease in the number of terraces between the tributary confluences due to reduced bedload transport.

(3) Bedload clast lithologies are not as homogeneously mixed downstream as they are in temperate regions. If this finding is applied to Quaternary bedforms it can be assumed that this means that a contemporaneous terrace may not necessarily exhibit the same clast assemblage at all points downstream. In fact, a significant input of a sediment from a tributary may alter the downstream lithology of a terrace from its upstream counterpart. This means that terrace correlation on the basis of like lithological composition, as assumed in temperate regions, is subject to some problems in semi-arid regions. The problems in the correlation of terrace fragments in semi-arid areas on the basis of clast lithology as illustrated conceptually by Figure 3.21.

(4) Erodability should determine the relative abundance of lithologies present in terrace gravels. Therefore, if abnormally high levels of a certain lithology, which cannot be explained by erosion rate, are found within a terrace deposit then this

may reflect a significant single event occurring within the catchment or part of the catchment at this time.

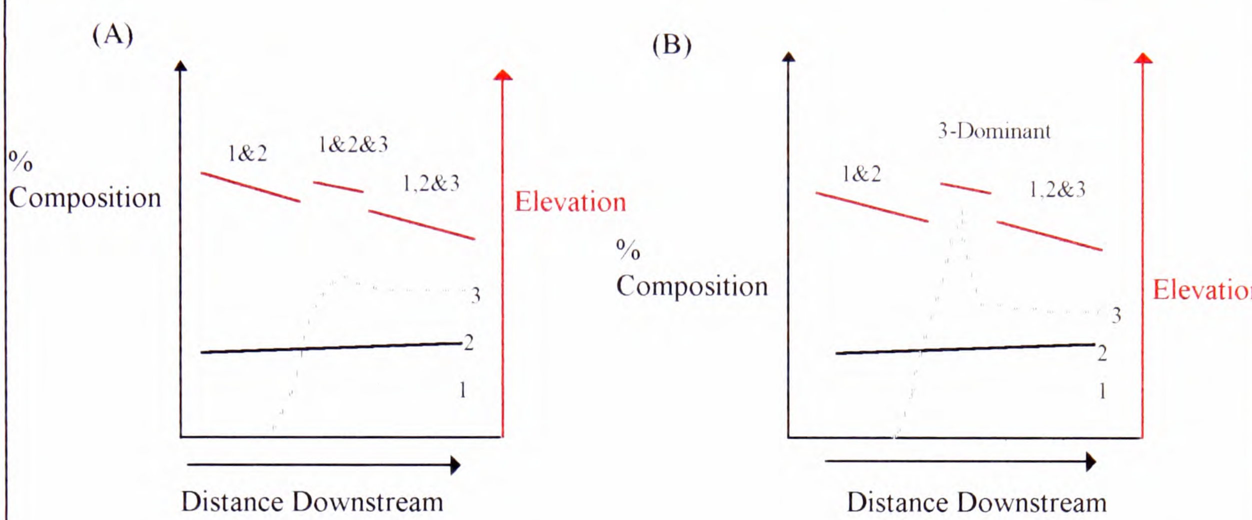


Fig. 3.21 Terrace graphs illustrating the percentage contribution of channel and tributary lithologies. 1, 2 and 3 are used here to represent different lithologies. (A) Shows the expected mixing of tributary lithologies in temperate regions and (B) shows the possible mixing in semi-arid regions.

(5) The ability of tributary channels to store sediment is a contributing factor to the rate at which it is introduced into the main channel at least in the short term. This again could hold significance to the proportions of different lithologies within a Quaternary terrace. High levels of a lithology close to a tributary junction may indicate that there has been a significant event within the tributary catchment washing out large quantities of sediment from the tributary stores. This obviously has to be considered with reference to factor (4).

Although preliminary these observations denote some of the problems in reconstructing drainage history in semi-arid regions in comparison to those in temperate areas. These factors illustrate that the assumptions applied for the correlation of terrace fragments in temperate regions, such as common downstream gradient and similar clast lithology, can not be relied on as a means of terrace correlation in semi-arid areas.

In the subsequent chapter, due consideration has been given to the problems identified here, prior to the determination of terrace groupings and whilst interpreting the processes that lead to the deposition of the terrace. For instance, terrace groupings were given a broader height range to make allowances for higher terrace fragments at tributary junctions and a knowledge of the location of tributary junctions and their potential sediment inputs was first established so that any anomalies in the Quaternary terrace fragments could be readily explained.

This chapter has illustrated 2 key factors: (1) That drainage reconstruction in semi-arid areas needs to be approached differently to reconstruction in temperate regions; and (2) that an understanding of the contemporary processes occurring within a catchment is an integral factor in the establishment of drainage history and the interpretation of Quaternary landforms.

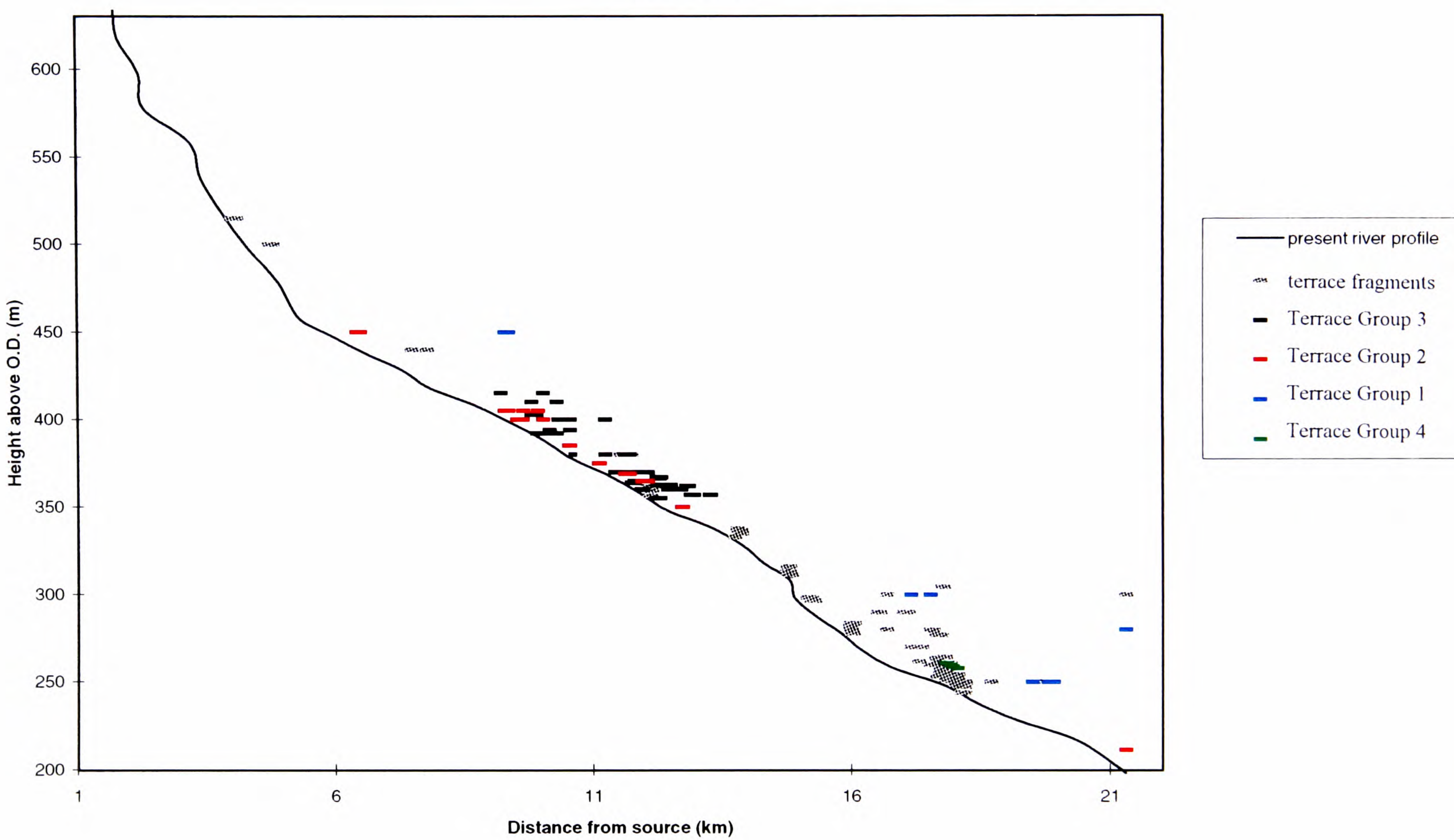
4.0 TERRACE DESCRIPTIONS

The purpose of this chapter is to document the distinctive features of the terraces identified in the Lucainena catchment. Over 70 terrace fragments have been recorded, however, on the basis of field observations it is possible to group most of these into four generic groups (Fig. 4.1). This is based on both elevation and sedimentary facies observations. Each member of one of these groups has a similar facies characteristic and broadly similar elevation. It was not possible to subdivide these groups further, not least because of the difficulties in terrace correlation caused by the semi-arid nature of the drainage basin as discussed in the previous chapter.

As can be seen from Figure 4.2 there is some overlap between the maximum and minimum heights for some of these terrace groups. However, as this chapter will show, the overlap occurs between terraces with significantly different sedimentological characteristics, such as Terrace Group 1 and 3, so the fragments can easily be matched with the appropriate terrace group on this basis. There are several explanations for the height variations amongst individual terrace groups: (1) floodplains from which terraces are cut have both cross valley and down valley gradients. Consequently terraces cut to different levels may have different elevations (Fig. 4.3); (2) some of the terraces made up of softer lithologies have been subjected to post subsequent degradation following formation; and (3) terraces at tributary junctions may have a greater elevation as discussed in chapter 3.0. The issues of terrace affinity/correlation are discussed where they arise in the description of each of the four generic terrace groups within this chapter. There are some isolated fragments which do not fit into any of these four generic groups despite appearing at similar heights due to dissimilar sedimentological characteristics.

Each of the four generic terrace groups will now be identified and described in detail in terms of its morphology, sedimentology and other distinctive features whilst taking into account the factors described in chapter 3.0. In the subsequent Chapter, 5.0, the drainage history of the Rambla de Lucainena will be established by identifying the relationships of these terrace groups.

Fig. 4.1 Terrace distribution graph showing the generic terrace groups of the Rambla de Lucainena



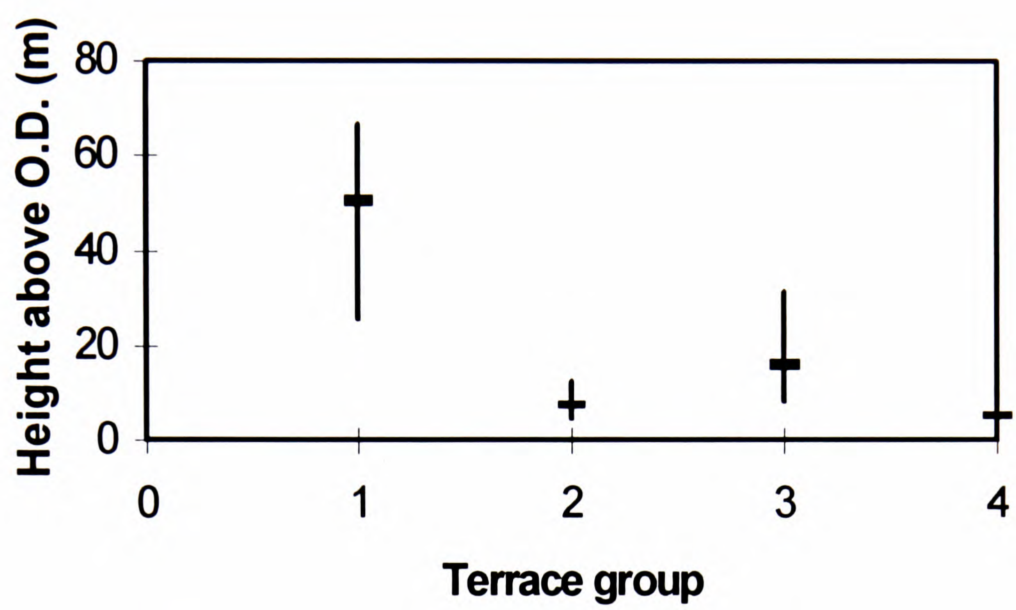


Fig. 4.2 Height ranges of the main terrace groups. The mid-point on each of the bars shows the average height and the vertical lines extend to the maximum and minimum heights recorded for each terrace group

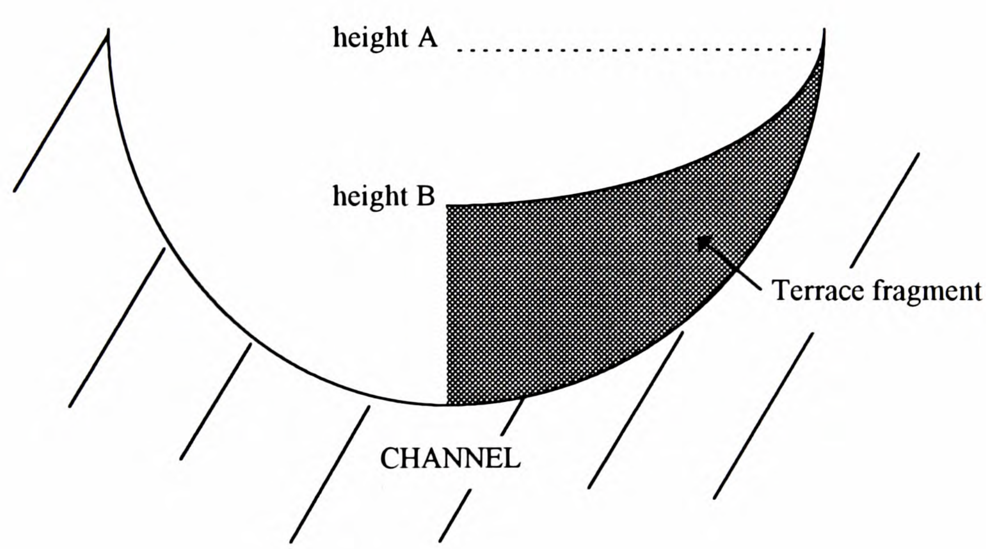


Fig. 4.3 Schematic diagram to show that terraces curve towards the river bed illustrating that two different heights A & B can be obtained for the same terrace fragment.

4.1 TERRACE GROUP 1

4.1.1 Morphology

This generic terrace group forms the highest terrace identified within the Lucainena catchment (Fig. 4.2). It consists of a thin calcrete layer deposited on the top of flat hills. Fragments have been identified over 8 km starting from just below the Rambla Honda tributary junction (Fig. 4.4). The maximum height of this terrace group above the present river bed is 62.5 m downstream with a minimum height of 27 m (Figure 4.2-inset 2). The maximum thickness of this terrace group is 0.5 m and in some instances is only observable as a flat bench level on top of hills, the terrace deposit being absent.

4.1.2 Sedimentology

The sedimentological composition of this terrace varies over distance and only a few sites were accessible for detailed identification due to the weathered nature of these deposits. It is generally clast supported and the major constituents were clasts of fossiliferous limestones, Tortonian and Pliocene sediments and non-fossiliferous carbonate clasts with only low levels of schist clasts which are a dominant constituent of other terrace groups. Also found in low levels are clasts of fault zone breccia, ironstone and quartz. One site was identified as being suitable for detailed analysis in the lower part of the catchment (Figure 4.2), here clast counts (n=100) identifying lithology and the 3 orthogonal axes were carried out. Figure 4.5 shows the clast distribution at this site, as can be seen the Tortonian/Pliocene sediments are the most abundant with non-fossiliferous carbonate clasts and clasts of fossiliferous limestone also abundant.

Figure 4.6 shows the dominant b-axis frequency is between 41 and 50 mm. The maximum clast size is 140 mm with a minimum of 1 mm. The average Krumbein value was 0.65 showing a tendency towards a true sphere. The ternary particle form triangle illustrated in Figure 4.7 shows a wide spread of clast points and hence particle form across this terrace sample. To aid in the analysis, clast envelopes (lines enclosing all the points of a given lithology), were drawn around the plots of the main clast types, Tortonian/Pliocene sediments, fossiliferous limestone and non-fossiliferous carbonate clasts. There is a considerable amount of overlap for these different lithological envelopes with all the plots tending towards the top centre of the triangle. However, the Tortonian/Pliocene sediments and fossiliferous limestone tend to be more blocky in form, where as the non-fossiliferous carbonate envelope is more central indicating a less blocky clast form. These envelopes illustrate some differences in particle form on the basis of lithology but show a great deal of similarity which is probably due to the isotropic structure of the limestones and dolomites within these sediments, which enable fracture in all directions.

4.2.3 Age Relationships

Terrace Group 1 has been identified as the oldest terrace group in the Lucainena catchment. There are two reasons for this, firstly, it is identified at higher levels than any other terrace group in the catchment, and it would be expected that incision would create a flight of terrace levels reflecting the abandonment of the previous floodplain with the highest terrace level reflecting the oldest floodplain remnant. This is especially true in an uplifting catchment, such as this, where incision occurs more rapidly and height differences are enhanced. Secondly, only low levels of schist are identified within this terrace group, which is anomalous because schist is abundant in all other terrace fragments identified in the Lucainena catchment. This could indicate that the schist was not fully captured at the time of deposition of this terrace group, a possibility which will be explored further in Section 5.1.

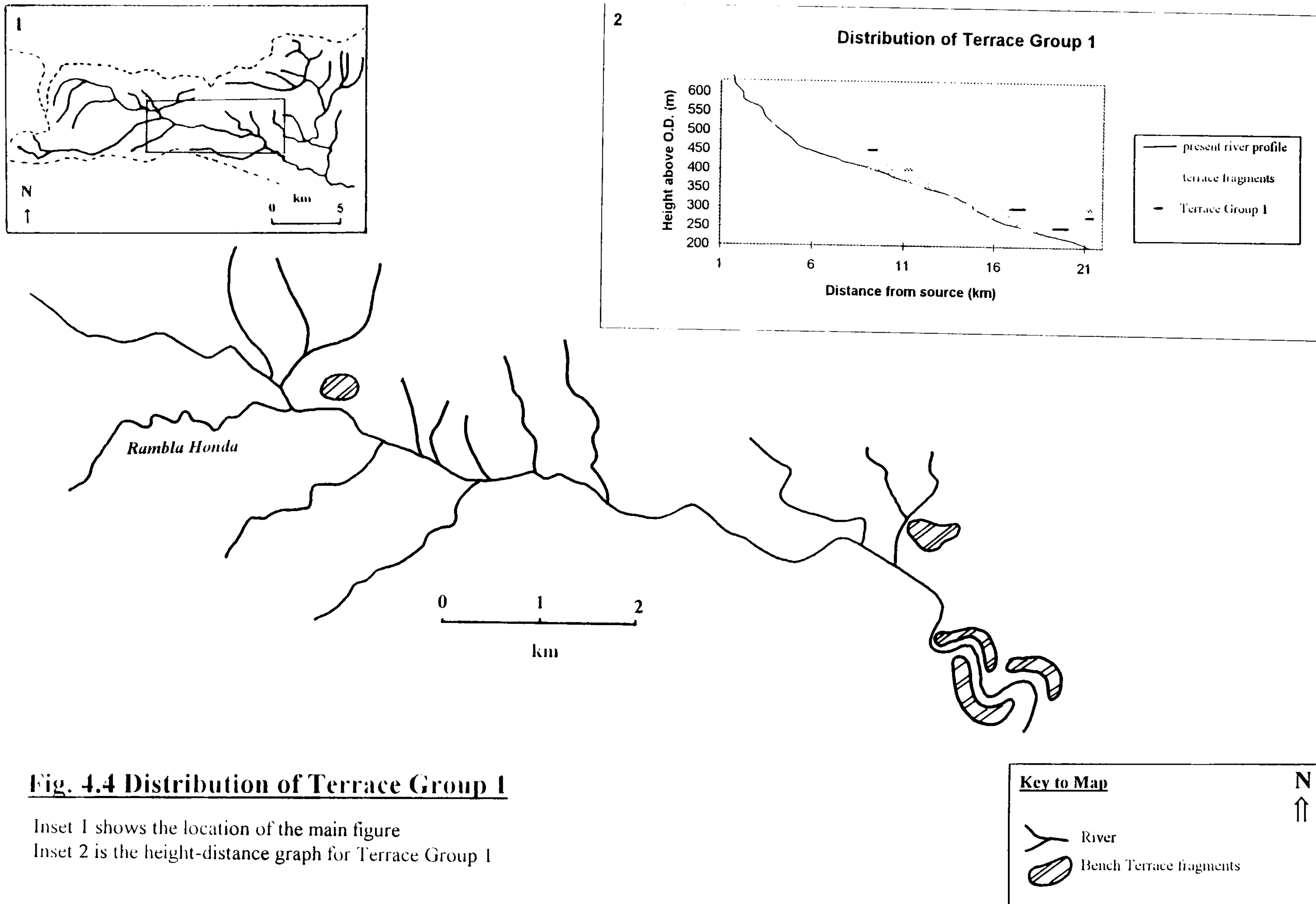


Fig. 4.4 Distribution of Terrace Group 1

Inset 1 shows the location of the main figure
Inset 2 is the height-distance graph for Terrace Group 1

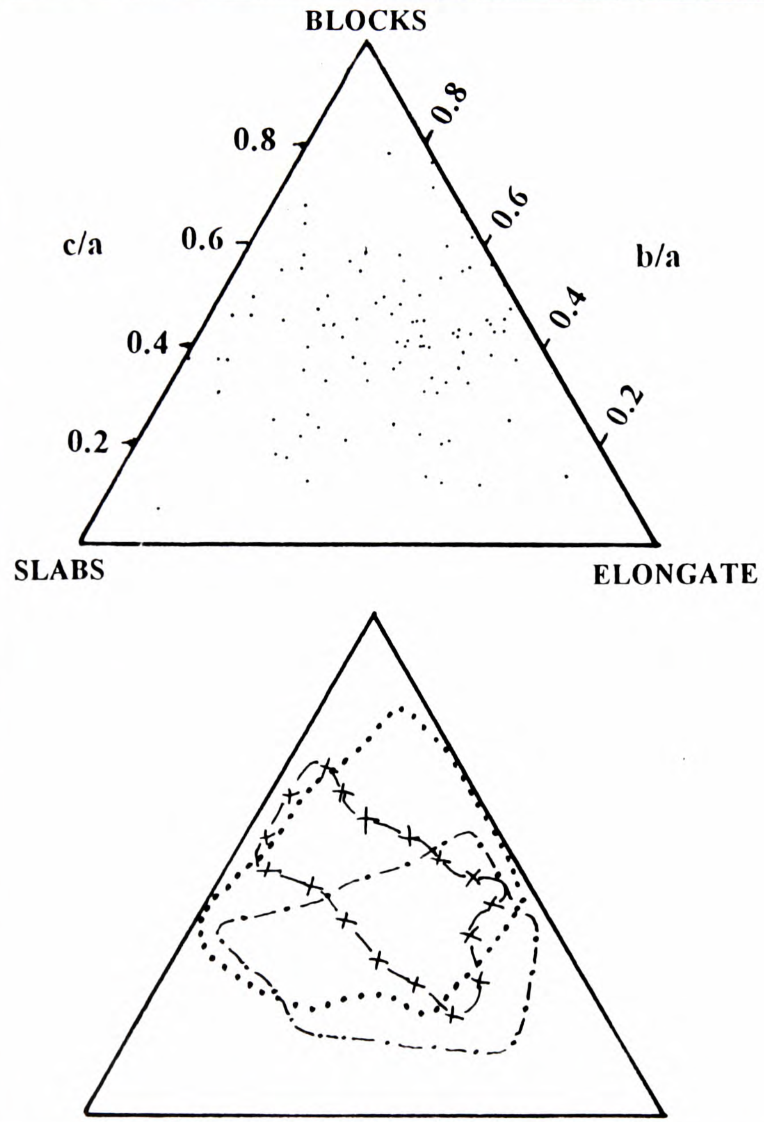


Fig. 4.7 Triangular plot of particle shape for Terrace Group 1. Facies envelopes show the shape of the dominant clast lithologies within this terrace level (•••••• = Tortonian/Pliocene sediments, -x-x-x = fossiliferous limestone, -•-•-= non-fossiliferous carbonate).

Fig. 4.5 Clast distribution for Terrace Group 1

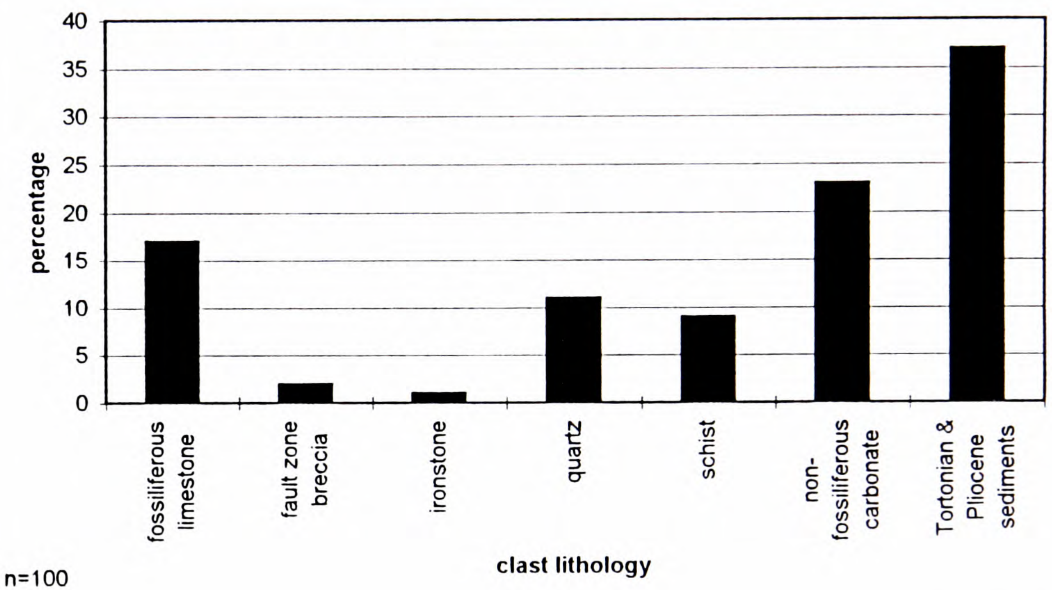
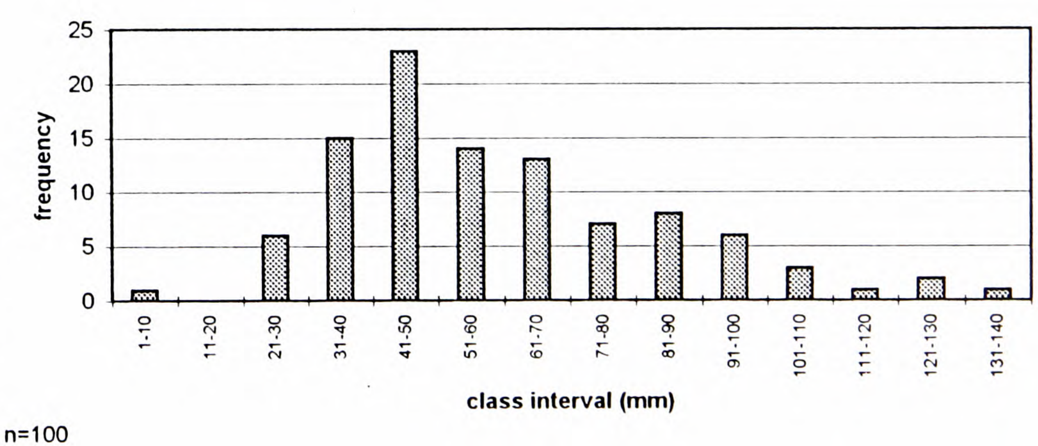


Fig. 4.6 Frequency distribution of b-axis for Terrace Group 1



4.2 TERRACE GROUP 2

4.2.1 Morphology

Base level change and incision resulted in a lower terrace group, Terrace 2. This consists of a cemented conglomerate and forms a consistent level with a maximum height of 12.5 m above the present river bed and is traceable for over 12 km (Fig. 4.8- inset 2), with the best developed sections just downstream of a major tributary junction. The main exposure of this terrace, Cem 1, is seen at the junction of the Rambla Honda and the main river, the Rambla de Lucainena (Fig. 4.8). This exposure forms a ledge some 12 m above the present river level and is approximately 20 m in width. The basal contact for this section is channel shaped and is carved into the underlying basement schists. The maximum thickness of this unit is 8 m and the minimum is 1 m.

4.2.2 Sedimentology

This terrace deposit is made up of three different conglomerate facies identified on the basis of particle size and lithology (Fig 4.8-Cem 1). It is extremely well cemented in its lower portion but, becomes less lithified up section. Each facies is structure-less with up to 80% composed of clasts gravel size or above and up to 40% sand matrix. The clasts are predominantly sub-rounded to angular. The features of these facies are consistent with those of debris flows because (Tanner & Hubert, 1991): (1) the facies exhibit poor sorting; (2) the clasts show a random orientation and (3) large clasts are projected above the tops of flows.

The overall clast assemblage is varied and includes schists, non-fossiliferous carbonates, fossiliferous limestones, fault zone breccia, quartz, Tortonian and Pliocene sediments.

The clasts within each of the debris flows are randomly orientated (Fig. 4.9). However, the direction of flow, west to east, has been established from provenance data. The lowest flow overlies a surface into the underlying basement schists. The other two flows exhibit an irregular non-erosional contact, from which it can be inferred that there was little time between the deposition of each of the debris flows, especially between the lower and middle facies, where gradational boundaries are evident along with some facies mixing. As there is no mixing between the middle and upper facies and no soft sediment deformation structures are seen, this implies that there was a non-depositional period prior to the deposition of the upper unit. This suggests that the middle unit may have been more cemented than the lower unit prior to deposition of the upper unit.

As can be seen from Figure 4.20 the most frequent b-axis measurement for all 3 facies was 10 to 50 mm with a maximum clast size of 750 mm recorded. The three facies are described below. For each of the facies units clast counts were taken (n=250), lithology and a and b axis were recorded for each count, c-axis could not be measured in this instance due to the cemented nature of the facies.

Facies A

The lowest unit, Facies A, is matrix supported and well-lithified with a main provenance from the Lucainena system, containing a range of clasts which can be identified as being mainly non-fossiliferous carbonate and Tortonian sediments (Fig. 4.10A). The base of this unit shows a grain flow of fine schist granules. As can be seen from Figure 4.11A average a/b axis ratios were plotted onto a single axis for each lithology within the facies with maximum and minimum error bars. Zero on the graphs indicates a bladed particle and 1.0 on the axis indicates a spherical particle. Schist clasts fall at 0.3 on the scale showing a more bladed appearance whilst the ironstone, quartz, Tortonian sediments, Triassic clasts and fossiliferous limestone fall around 0.6, showing a greater roundness. The more bladed appearance of the schist can be explained by its strongly foliated nature and the fact that it contains platy clay minerals. The greater roundness of the other clasts could be due to their more structure-less nature or in the case of the Tortonian sediments the rounded sand grains they contain.

Facies B

Facies B, is clast supported and well-lithified with a provenance from the Honda system indicated by the high schist contribution (n=250; Fig. 4.10B), derived from the basement highs. As shown in Figure 4.11B plots of a/b axis ratios revealed a similar pattern to Facies A with a noticeable anomaly being the fault zone breccia which falls at completely the opposite end of the scale showing a greater roundness in contrast to the bladed tendency of those in Facies A.

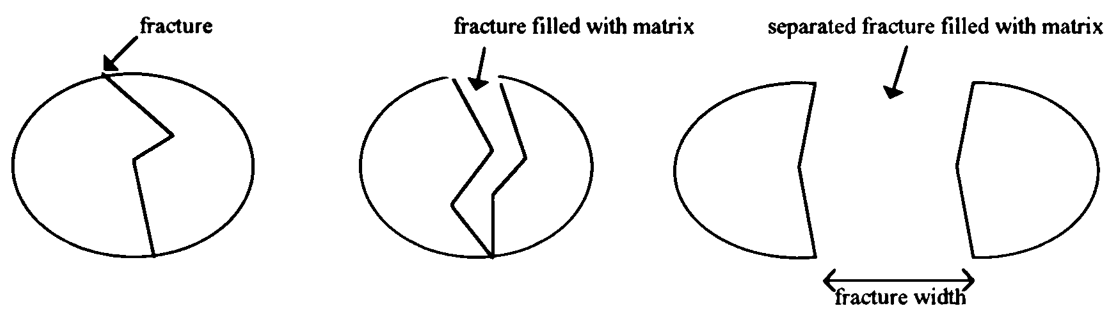
Facies C

Facies C, contains both clast and matrix supported gravels and is the least lithified of the deposits. The clast assemblage shows provenance from the Lucainena catchment, as with facies A, although it has a slightly higher proportion of fault zone breccias (n=250; Fig. 4.10C), which possibly indicates a further westerly headcut. The a/b ratio plots (Fig. 4.11C) showed similar plots to those of Facies A and B, but the plot of the fault zone breccia in this facies falls between the position of its plot in Facies A and B at just below 0.6. This appears to indicate that particle roundness in the case of the fault zone breccia is influenced by factors other than lithology, whilst with the other clast types lithology seems to be an important factor in particle roundness.

All three facies can be traced at sites up and downstream for over 12 km (Fig. 4.8), these did not exhibit all 3 facies levels but have been correlated with the most appropriate facies level on the basis of clast assemblage (n=100; Fig. 4.10D-I). Again a/b ratio axis (Fig. 4.11D-I) showed similar plot patterns with the exception of the fault zone breccia and in one instance, Cem 5, the plot of the schist clast which appears at the opposite end of the scale showing an uncharacteristic roundness (Fig. 4.11D). However, due to the smaller size of these clast counts this may be a less reliable result.

4.2.3 Other Distinguishing features

Fractured clasts and fractured clast pairs (Fig. 12) have been identified within this terrace level. The fractures within the clasts are uneven and show no preferred orientation (Fig. 4.9B). The fractures are only found within the clasts and are not apparent within the matrix. The fractures either cut across the full length of the clast (Fig. 4.13) or extend partially across it. Fractured clast pairs are intruded with matrix and usually contain more than one fracture set. The fracture patterns are radial and originate from a shatter zone which is usually the outer edge of the clast and are filled with matrix often containing host clast fragments and other debris (Fig. 4.14). The clast pairs and fragments can be traced to fit exactly back together on a 2-dimensional scale like a jigsaw puzzle into parent clasts (Fig. 4.15). Often fracture patterns were associated with areas where the clasts were so closely packed that clast contacts could be seen.



A) Fractured clast B) Fractured clast pair C) Separated fractured clast pair

Fig. 4.12 Diagram summarising the terms used to describe clasts with fracture within Terrace Group 2

The exposure which shows the greatest number of fractured clasts and clast pairs is found at the junction of the Rambla de Lucainena and the Rambla Honda (Fig. 4.8). The terrace remnants close to this junction, to a maximum distance of 3 km downstream show high levels of fractured clasts and clast pairs. These remnants mainly consist of Facies B and C, with the fractured clasts and clast pairs within them only occurring on small tributary junctions.

The number of paired fractures were also analysed within clast counts, with particular emphasis on clast type, fracture width and the axis of fracture, to see whether any preference could be identified. Clast counts were taken to obtain the same information at the smaller sites (n=100). This clast analysis demonstrated that the fracturing occurs irrespective of clast lithology and shape. Under close examination a few of the clast fragments could be identified as coupled pairs to a maximum separation of 750 mm. In addition some halves of fractured clasts were observed which could not be traced back to there other halves. The fracturing was generally not related to clast size, although, it is predominant in clasts with a long axis of less than 200 mm. 80% of the clasts with fracture showed a preference for fracture along their short axis.

Facies A

At the main site of clast fracture Facies A, the lowest facies in Cem 1, contained the largest proportion of fractured clasts and clast pairs, with more than 50% of the clasts showing fracture (Fig. 4.16). The clasts within this lower unit are generally matrix supported, although, with some of the larger fractured clasts, point contacts can be seen between the clasts. Figure 4.17 shows that fracture seems to be independent of clast type with the average number of fractures per clast being similar for each lithology. Surprisingly, the more friable schist clasts appear to show a slightly lower number of fractures per clast than the more dense clasts such as fault zone breccia and fossiliferous limestone. As can be seen from Figure 4.18 the average fracture width for the quartz clasts is significantly larger then any other clast type at over 40 mm. Fossiliferous limestone, ironstone and the non-fossiliferous carbonate clasts also show a reasonable size fracture width of 10 to 20 mm whilst schist exhibits the smallest fracture width at under 50 mm.

Facies B

Although the middle facies at Cem 1, Facies B, contained far fewer fractured clasts and clast pairs with just under 14% of the clasts showing fracture (Fig. 4.16), the fractures within this facies are also significant. This unit is more clast supported with a higher percentage of clast contacts than its lower counterpart with roughly 50% of the clasts showing point contacts. As can be seen from Figure 4.19 clast fracture within this facies was not apparent in all clast types but again average fracture widths were smallest in the schist clasts and greatest in the harder clast types, although overall were smaller than those of Facies A.

Facies C

In the upper facies at Cem 1, Facies C, only 12% of the clasts were fractured (Fig. 4.16). More point contacts are seen than in Facies A and B, roughly 60%, so a greater degree of clast support can be surmised. Figure 4.19 shows that like Facies

B not all clast types show fracture and again that the denser clast types show the maximum average fracture widths and the schist the smallest.

A low fracture percentage (20-22%) is seen within terrace remnants for a 2 km stretch downstream of this section, with clast and clast pair fractures mainly occurring on small tributary junctions within these remnants. To determine whether this smaller clast fracture percentage would be present as background fracture in most cemented conglomerates, other unrelated cemented terrace levels of the Sorbas basin were also analysed (A and B terraces; Harvey & Wells, 1987). Only 4% to 5% of the clasts showed some form of fracture, predominantly in the friable schists and the easily fractured quartz, but none of the fractured clasts were clast pairs infilled with matrix. Therefore, the amount and type of fracture identified within these facies is significant.

As can be seen from Figure 4.19, fracture analysis of Cem 2 to 7 also shows that not all clast types show fracture, however, overall no clast preference is seen throughout the samples. Overall the average fracture width for these deposits is smaller than that of Facies A and is smallest in the friable schists clasts.

Thin sections were taken from 6 samples and studied to visually check for differences in cementation of the matrix across the facies types and within fractured and unfractured specimens, in order to identify or eliminate cementation as a possible cause for the clast fractures. The cement was micrite (80 %) and was consistent across all sites, with no anomalies present in the facies with fractured clasts. Some secondary calcite replacement of the cement was seen along the rims of some of the clasts and within some of the microfractures suggesting slight diagenesis, and there was evidence of some grain coating that had undergone calcite replacement most probably occurring prior to cementation, as the cement was unaffected. These were the only obvious diagenetic features seen within the sample. Close attention was also given to matrix composition within and around the fractures, to check for any textural features suggesting localised liquefaction of matrix. However, no significant textural difference was identified. The porosity of the clasts was visually estimated and varied with the different clast lithologies, with the sandstones and limestones showing a high porosity and the quartz and ironstone showing a low porosity. Because fractures were found in both porous and non-porous clast types no relationship between porosity and fracture can be identified. No microfabric within the conglomerates in the form of cleavage or crenulation was found suggesting no apparent tectonic influence.

4.2.4 Age Relationships

Terrace Group 2 is identified as the second oldest terrace group in the Lucainena catchment. There are two main reasons for this, firstly, it occurs at a lower elevation than Terrace Group 1; and secondly it is buried by Terrace Group 3, which will be further discussed in section 4.3.4.

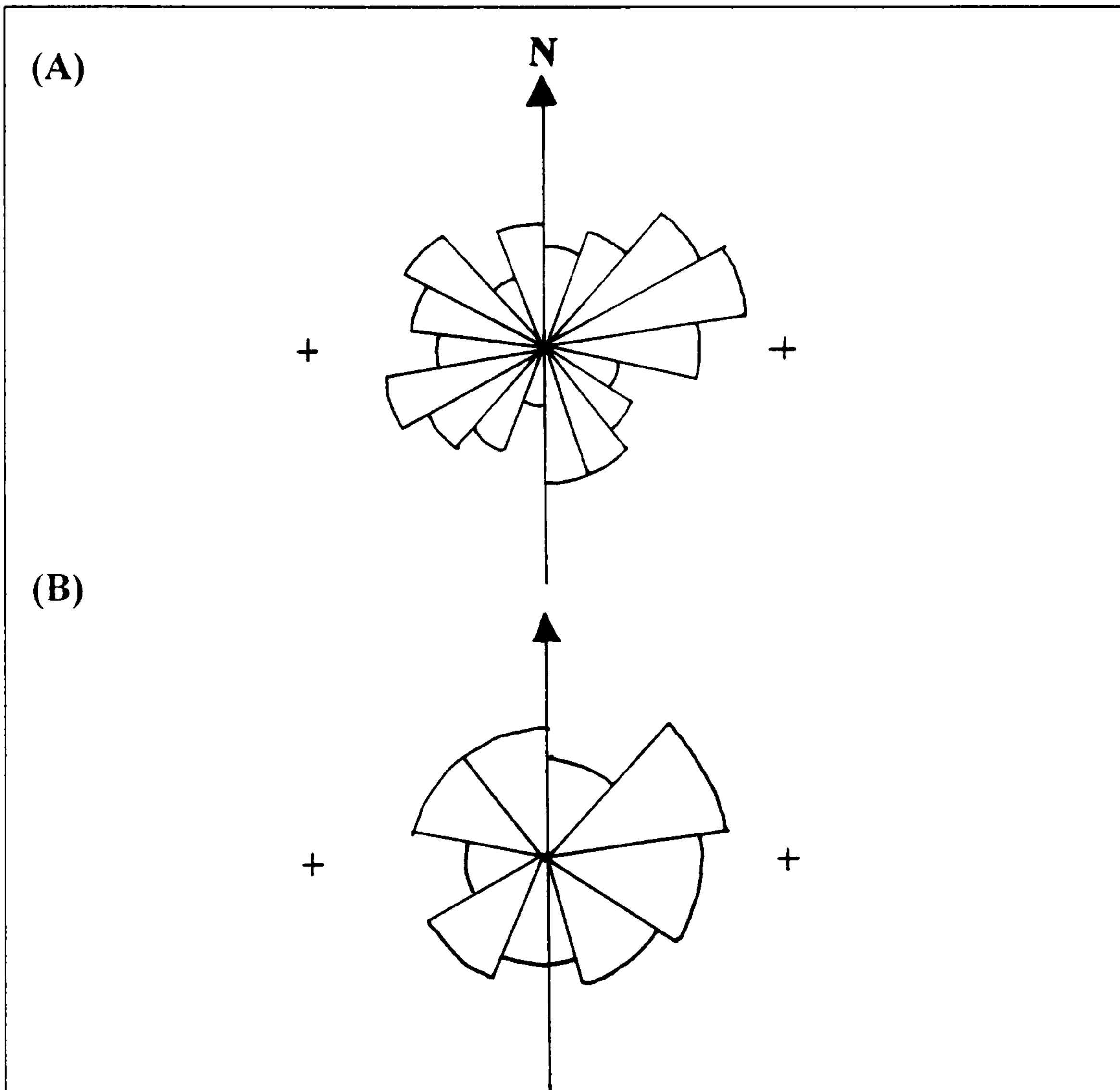


Fig 4.9 Rose diagrams showing (A) the orientation of clasts in the debris flows of Terrace Group 2 and (B) the orientation of clast fractures within the debris flows of Terrace Group 2. Note that no preferential orientation is seen in either.

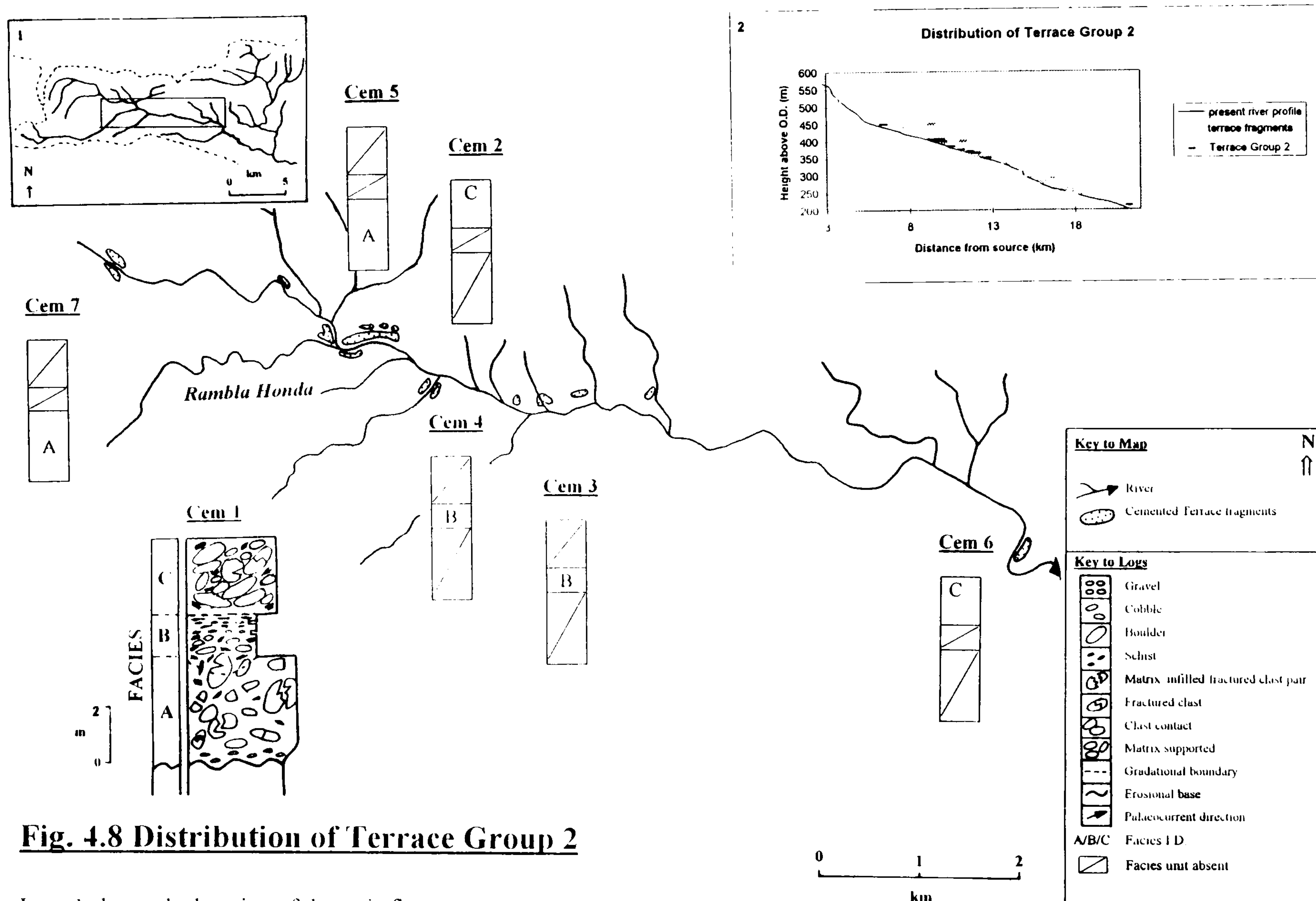


Fig. 4.8 Distribution of Terrace Group 2

Inset 1 shows the location of the main figure
Inset 2 shows the height-distance graph for Terrace Group 2

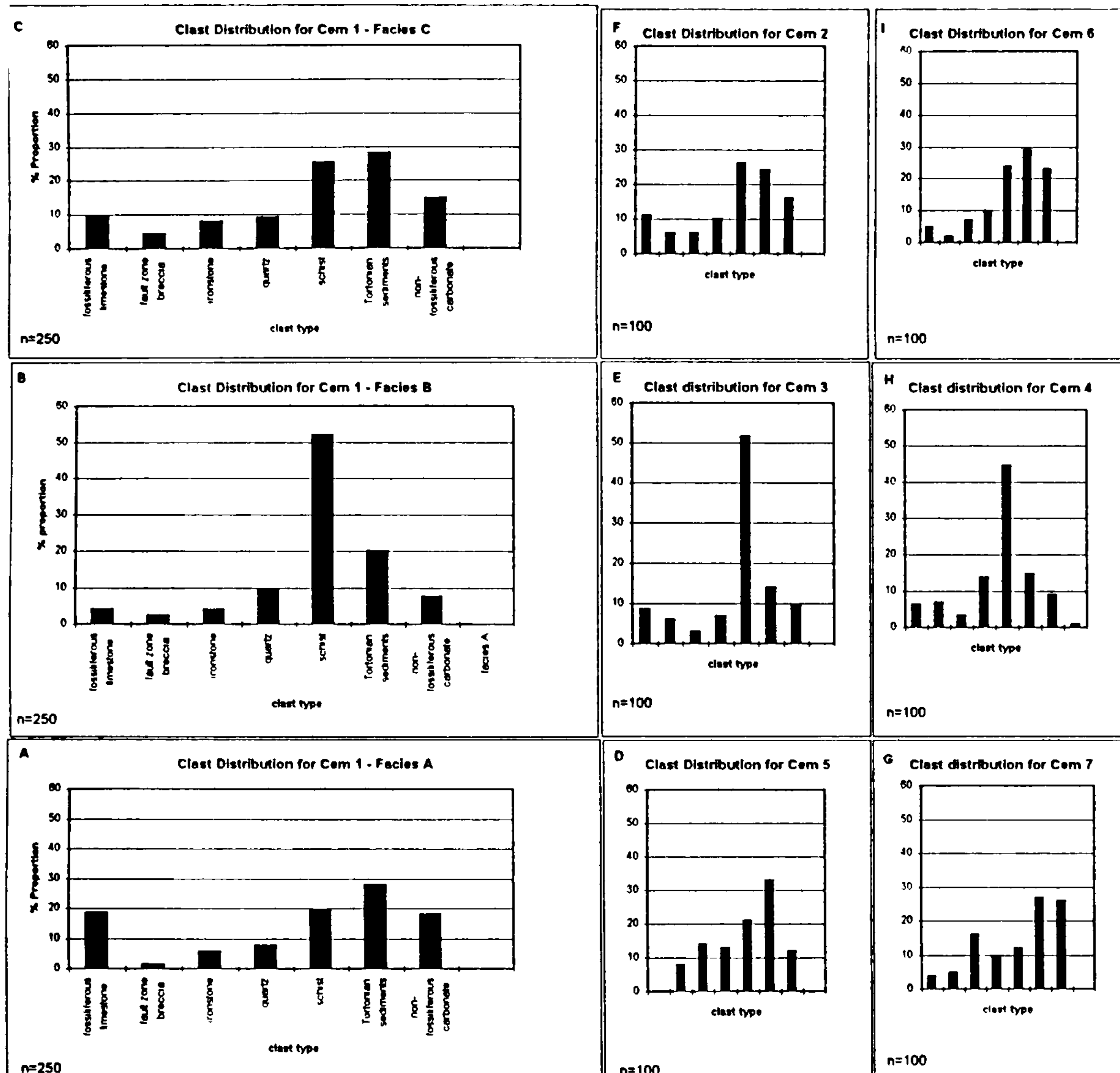


Fig. 4.10 Clast Distribution for Terrace Group 2.
Cem 1-7 are different sample sites located on Figure 4.8. Similar facies are lined up horizontally i.e D & G belong to Facies A. Facies have been grouped on the basis of similar clast distribution Note that the Tortonian sediments in (I) also include some Pliocene sediments as Cem 6 is found in the downstream section of the Lucainena catchment.

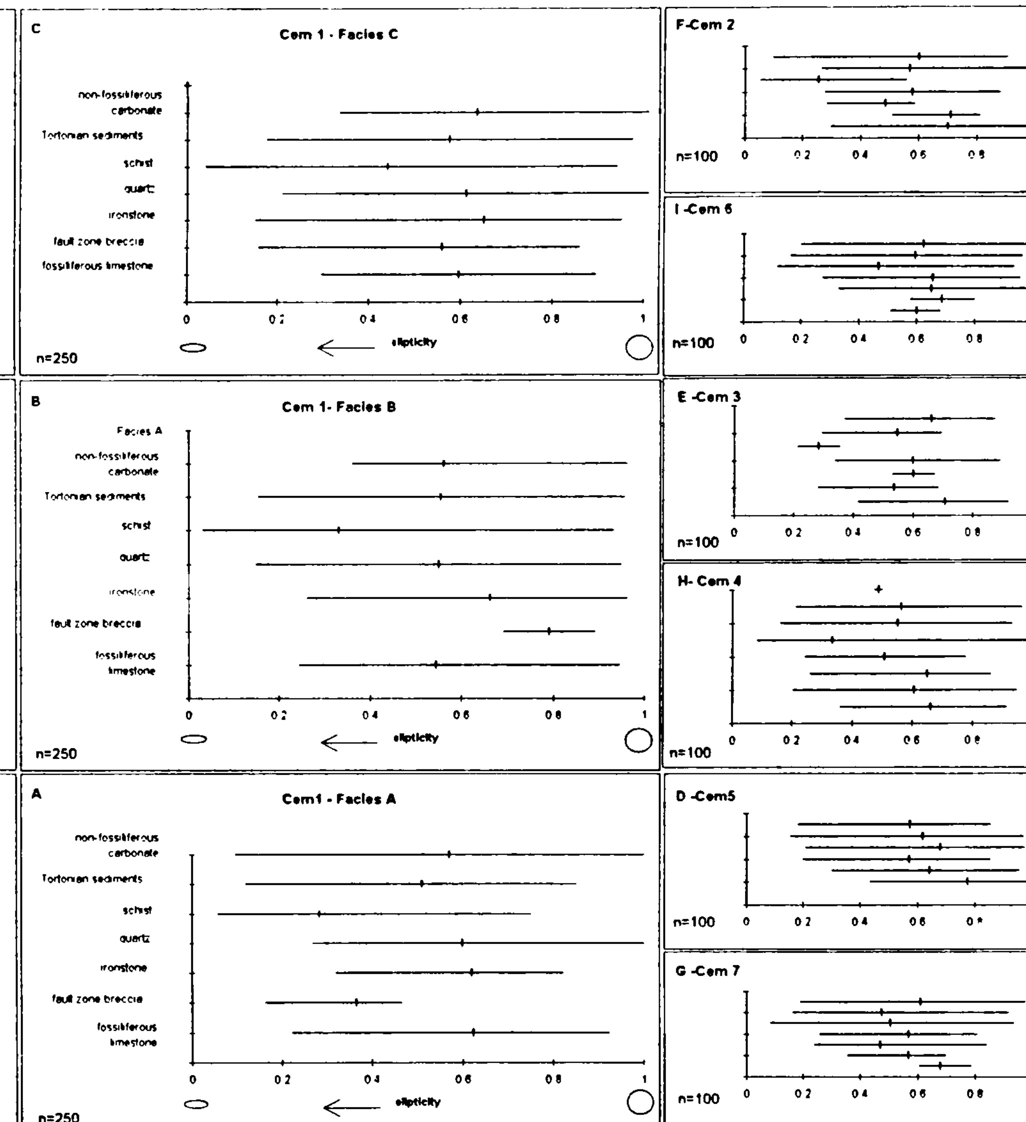


Fig. 4.11 Particle roundness for Terrace Group 2
Tick marks indicate the average eliptcity (b/a) for each clast type, the horizontal bars show the max and min values. Cem 1-7 are different sample sites located on Figure 4.8 and have been grouped according to similar clast distribution as shown in Fig 4.10

Fig. 4.13 Fractures cutting across the full length of a clast.
Lens cap = 52 mm

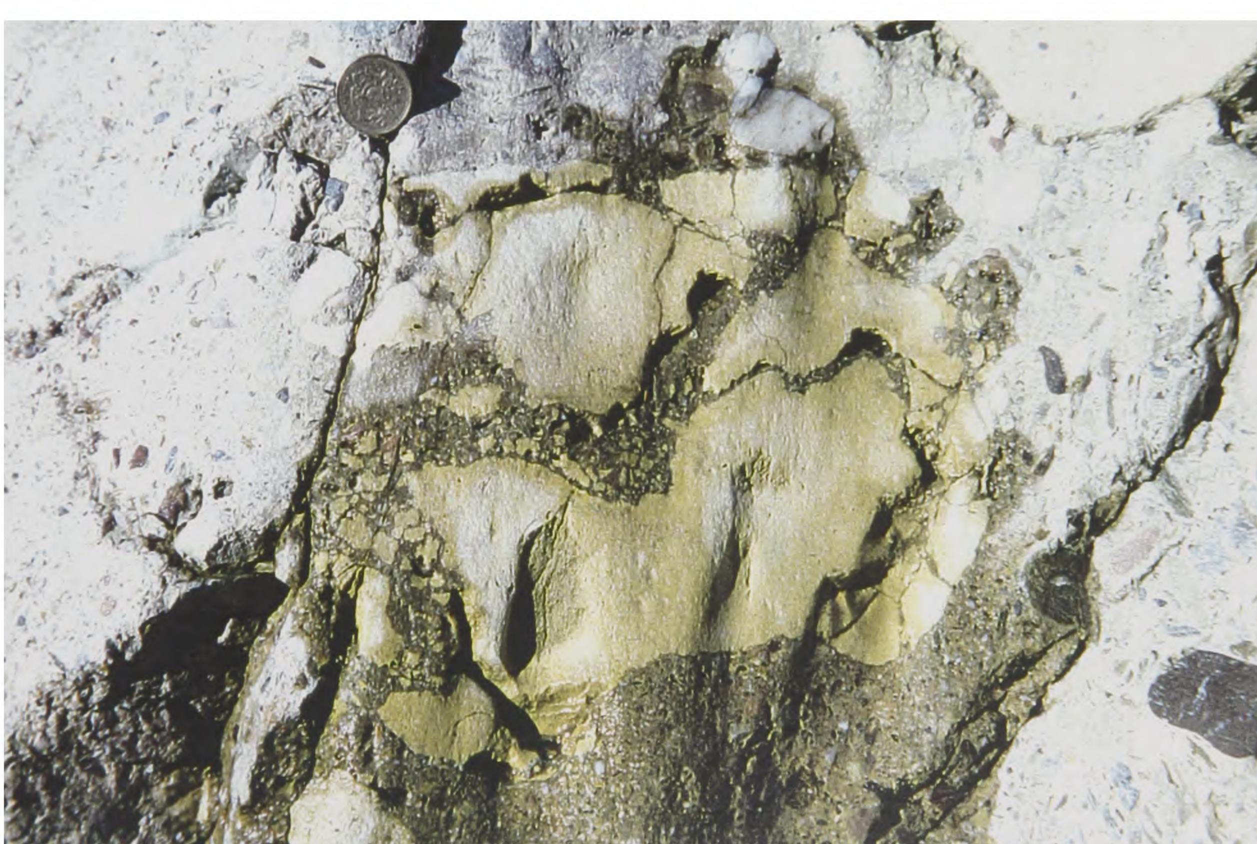


Fig. 4.14 Fractured clast pair infilled with matrix and other debris
Pound coin for scale. Note that part of the section has had water poured on it to enhance the detail.

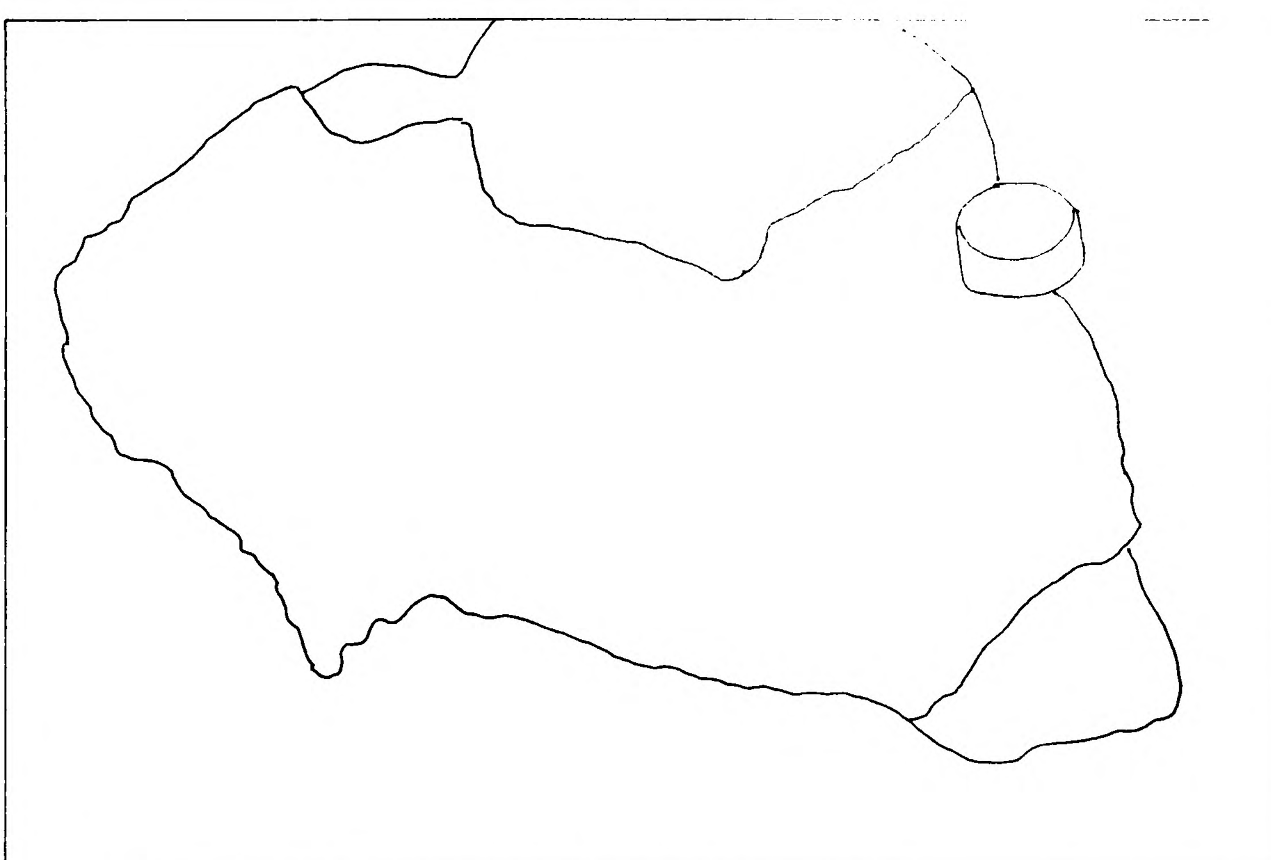


Fig. 4.15 Fractured clast pair illustrating that clast fragments can be traced back together on a 2 dimensional scale. Tape measure diameter = 50 mm

Fig.4.16 Percentage of total clasts exhibiting fracture within each Facies of Cem1

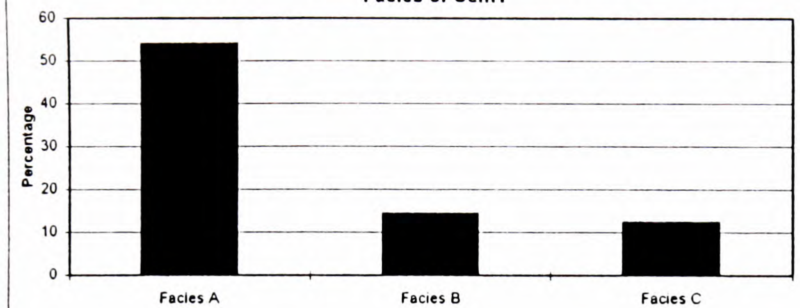


Fig. 4.17 Average No. of fractures per clast for each clast type in Facies A (Cem 1)

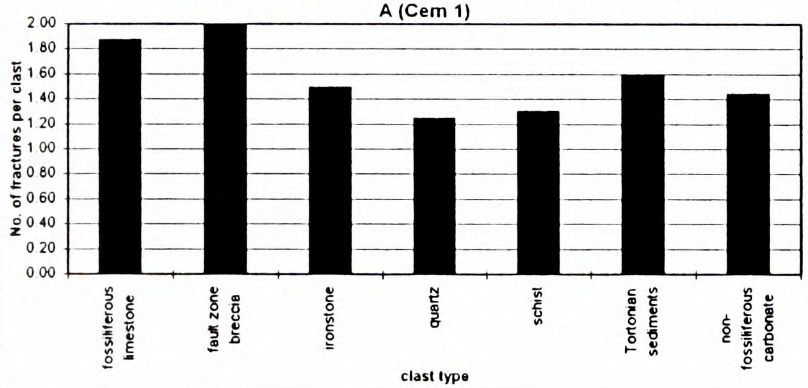


Fig. 4.18 Fracture widths for different clast types for Facies A (Cem 1)

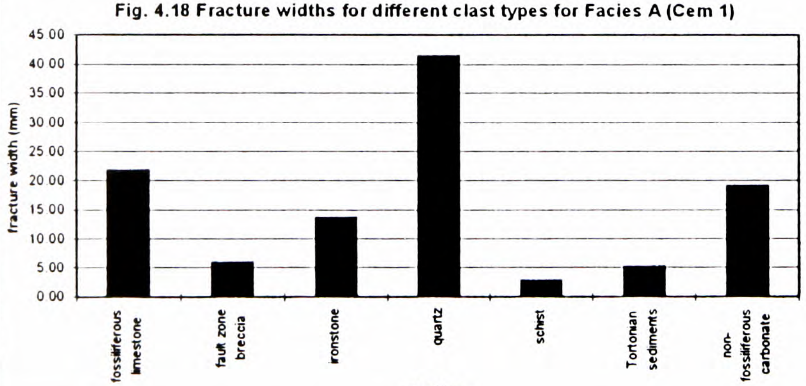
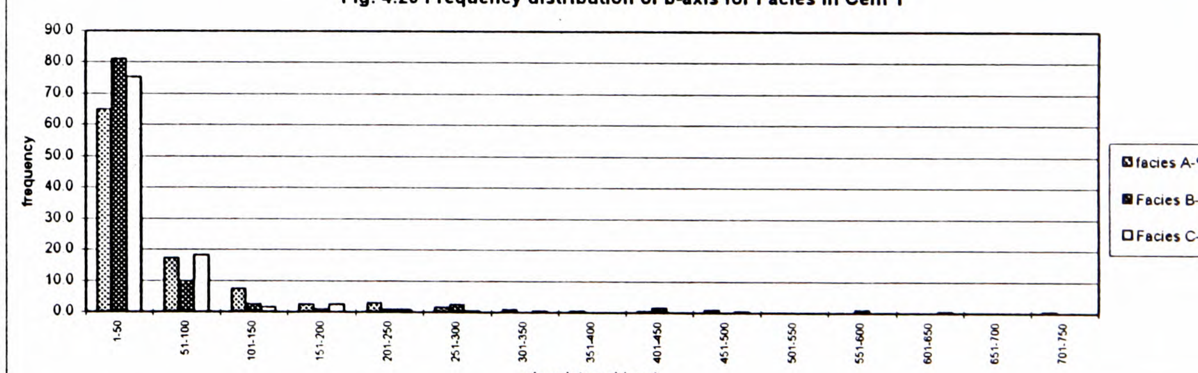


Fig. 4.19 Clast fracture lithology and fracture widths for Cem1-7

Terrace fragment	Facies	% clast fracture	lithology	Average fracture width (mm)
Cem 1	B	14	Faultzone breccia	22.5
			Quartz	6.0
			Schist	5.0
			Triassic clasts	10.5
Cem 1	C	12	Fossiliferous limestone	13
			Quartz	1.0
			Schist	1.0
			Triassic clasts	3.0
Cem 2	C	20	Quartz	1.0
			Schist	1.6
			Tortonian sediments	6.7
Cem 3	B	3	Faultzone breccia	2.0
			Quartz	30.0
			schist	1.0
Cem 4	B	22	faultzone breccia	2.3
			Quartz	1.8
			Schist	0.4
			Tortonian sediments	1.5
			Triassic clasts	1.0
Cem 5	A	1	Schist	2.0
Cem 6	C	1	Triassic clasts	6.0
Cem 7	A	3	Tortonian sediments	1.7

Fig. 4.20 Frequency distribution of b-axis for Facies in Cem 1



4.3 TERRACE GROUP 3

4.3.1 Morphology

This generic terrace group forms a thick consistent unit and extends downstream for 5 km. The lateral extent of this terrace group is shown in Figure 4.21. Its first exposure is seen as the main channel widens just above the Rambla Honda tributary junction (9 km from the source of the Rambla de Lucainena), sections are abundant and well developed just below the channel confluence and extend until they reach a narrow constricting gorge 14 km from the source. The terrace cannot be traced further downstream after this gorge. As can be seen from Figure 4.21, the terrace group appears to be split into two levels reaching a maximum height of 31.25 m above the present channel. The base of the terrace ranges from 8 to 10 m above the existing channel and is usually perched on bedrock. The minimum height of the terrace group is 8 m. The tops of the terraces are heavily eroded and considerable difference is seen between the heights of the fronts and backs of the terrace.

4.3.2 Sedimentology

This terrace group consists predominantly of brown/grey fine sands interbedded with clays and coarser gravel and pebble/cobble beds which are laterally discontinuous as shown in the log sections of Figure 4.21. These beds do not show any consistent cyclic pattern and can not be traced across any distance. The logs, Agg 1 to 4 shown in Figure 4.21, show small coarsening upwards cycles indicating that sedimentation was rapid. The logs also show that there is a fining in the sections downstream (eastwards) with Agg 1 and 2 consisting of predominantly coarser gravel to cobble clasts, and Agg 3 and 4 being predominantly fine to medium sands. This rapid interchange of particles from coarse to fine grained over small distances suggests that this terrace has been deposited rapidly with considerable variation in flow regime and is consistent with frequent flooding episodes, perhaps associated with more perennial flows where the coarse channel sediment becomes over loaded with fine grained over-bank sediments.

The gravel beds consist of schists and quartz clasts, Tortonian sediments, fault zone breccias and non-fossiliferous carbonate clasts. These beds are mainly clast supported with the general shape of the clasts exhibiting a 3:1 ratio of the a: b axis. The majority of the clasts are sub-rounded to sub-angular, although the schists are lenticular in shape. Imbrication was seen in some of the gravel beds from which palaeocurrent measurements (Fig. 4.21) were taken revealing a past drainage direction almost consistent with that of the present day Rambla de Lucainena.

Clast counts (n=250) were taken at 3 of the 4 log sites to determine the lithological composition of this terrace group. As can be seen from Figure 4.22A-C the schist clasts are the dominant lithology by a large majority, quartz clasts and Tortonian sediments are also abundant and non-fossiliferous carbonate clasts become slightly more abundant downstream (Fig. 4.22C).

The average Krumbein value for Agg 1 was 0.526, for Agg 2 it was 0.539 and for Agg 3 it was 0.578. Figure 4.23 shows the dominant b-axis frequency for Agg 1-3 is 11 to 20 mm. The maximum clast size is 111 mm with a minimum of 1 mm. The ternary particle form diagrams shown in Figure 4.24 show that the clast points for this terrace plot in all parts of the triangle. Clast envelopes were drawn for the main clast types, schist, Tortonian sediments and non-fossiliferous carbonate clasts. These envelope shapes were similar for Agg 1, 2 and 3 and there was some overlap of different lithologies. The schist envelope exhibits a particle form of elongate to slab shape plotting towards the base of the triangle, whilst the Tortonian sediments plot in the centre of the triangle equidistant from all the corners showing a mixture of blocky, slab and elongate form. The non-fossiliferous carbonate clasts on the other hand plot between the block and elongate axis on the triangle indicating a combination of these two particle forms. These ternary diagrams illustrate again that lithology is an important factor in determining particle shape.

4.3.3 Other distinguishing Features

A: Geochemistry

Geochemical analysis was carried out on samples of fines (Sample 1-5 shown in Fig. 4.21) to back up the analysis of clast count data on the coarser sediments. This gave trace element and oxide data which established a geochemical signature for this generic terrace group. The secondary purpose of this type of analysis was to attempt terrace correlation to prove that this group of terrace remnants had been correctly identified as a generic group and to see whether other unestablished terrace remnants were related to this group. The use of this type of geochemical analysis as a correlation tool for terraces is not well documented in the literature, as other types of analysis such as heavy mineral analysis are preferred for provenance and correlation studies (Wielchowsky & Stow, 1975; Morton, 1991; Chen *et al.*, 1994; Hallsworth *et al.*, 1996). The aim here is to show the usefulness of this tool and to identify this method as an area for which further research and investigation should be undertaken.

As can be seen from Figure 4.25A the geochemical signature of the oxides in samples 1-5 is almost identical, with the major peak occurring at SiO_2 which is to be expected due to the large sand constituent. Other minor peaks were noted at Al_2O_3 and Fe_2O_3 (T). The trace element profiles were more useful because these elements are found in relation to more specific substances. As can be seen from Figure 4.25B these also showed similar trends with major peaks occurring at barium, strontium and zirconium in all samples. Zirconium and barium are found in relatively high concentrations in carbonates (Krauskopf, 1979; Evans, 1993) and sandstone (Krauskopf, 1979) and strontium is found in association with dolomites (Tucker & Wright, 1992).

Due to the similar geochemical signatures it is likely that these terraces are related or are at least sourced from similar sediments or areas.

B: Microfossils

All of the samples, 1 to 5, were also processed to look for microfossils. All samples showed a high proportion of reworked foraminifera and a few reworked ostracods. This assemblage of reworked material included the foraminifera genera of *Globigerinoides*, *Orbulina*, *Nonionina* and the ostracod genus *Aurila*. These genera are consistent with being sourced from older Neogene strata. As well as these reworked genera a few genera of contemporaneous ostracods were identified. These were clearly distinguishable from the reworked specimens which showed varying preservation, broken or corroded tests and infilled tests displaying many different colours, all features suggesting displaced or reworked fossils (Cita & Colombo, 1979). A total of 120 specimens of *in situ* ostracods were identified across all of the 5 samples, these included 8 genera: *Cyclocypris*, *Potamocypris*, *Candona*, *Psychrodromus*, *Ilyocypris*, *Cypris*, *Heterocypris* and *Trajancypris* (?). Of these genera the first 6 were all present in sample 3, located in Figure 4.21, which showed the most diverse and abundant *in situ* fossil assemblage. All of the samples contained at least some of these genera indicating similar environmental conditions. These genera all indicate a freshwater palaeoenvironment consistent with temporary water bodies such as floodplain pools that dry out within a couple of months, there is an absence of any genera which would suggest permanent water bodies (Horne, *Pers. com.* 1997). One genera, *Psychrodromus* is known to live in flowing water bodies, such as springs. Insufficient specimens were found to identify these genera down to species level, however, this preliminary investigation has revealed an interesting assemblage of Quaternary freshwater ostracods in SE Spain, which is an under researched area, definitely worthy of further study.

4.3.4 Age Relationships

Terrace Group 3 is identified as being younger than Terrace Group 2 despite its higher elevation. This is because the aggradational fines of Terrace Group 3 completely bury the cemented conglomerate of Terrace Group 2, and there is no erosional contact between them.

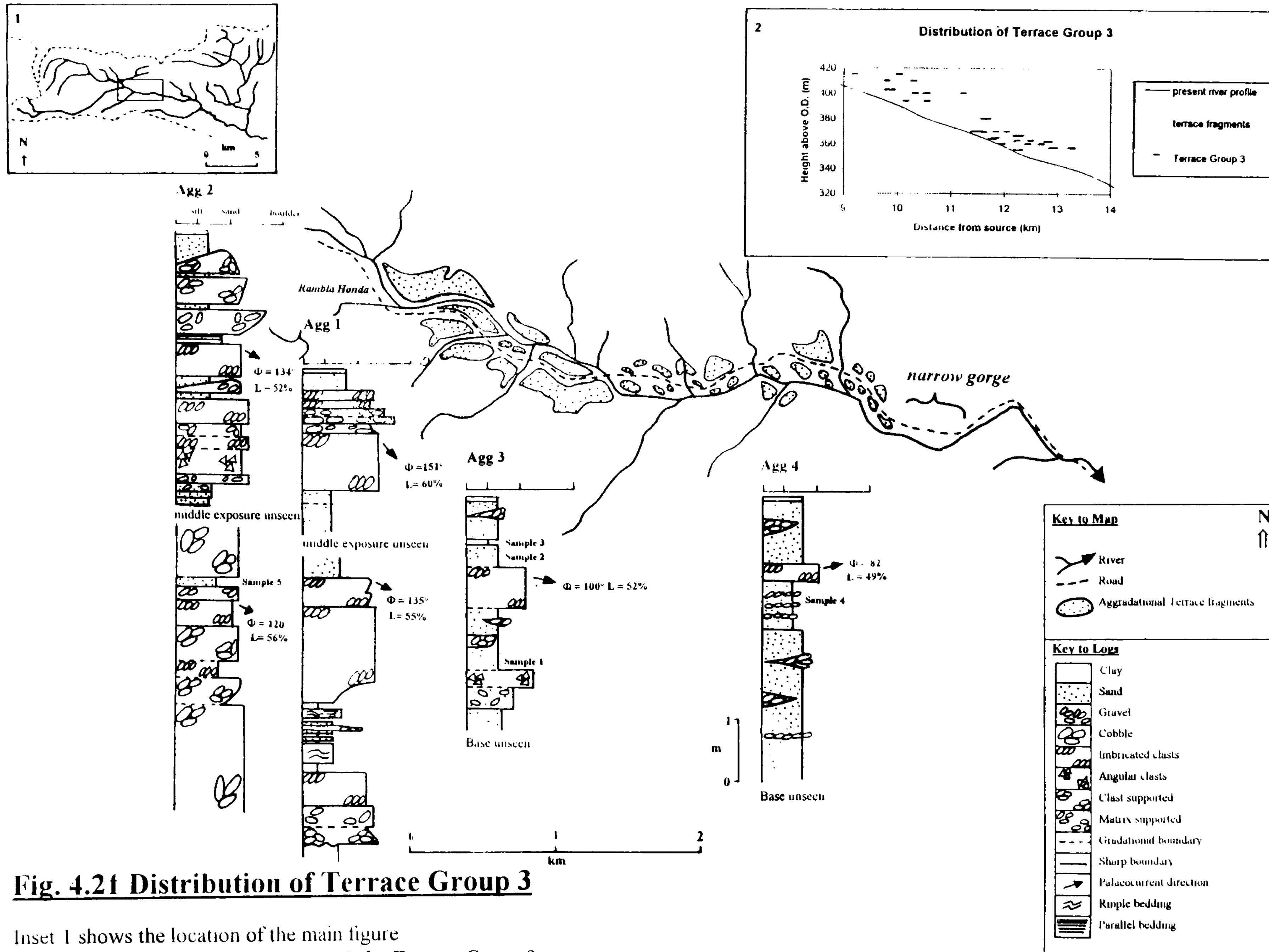


Fig. 4.21 Distribution of Terrace Group 3

Inset 1 shows the location of the main figure
Inset 2 shows the height-distance graph for Terrace Group 3

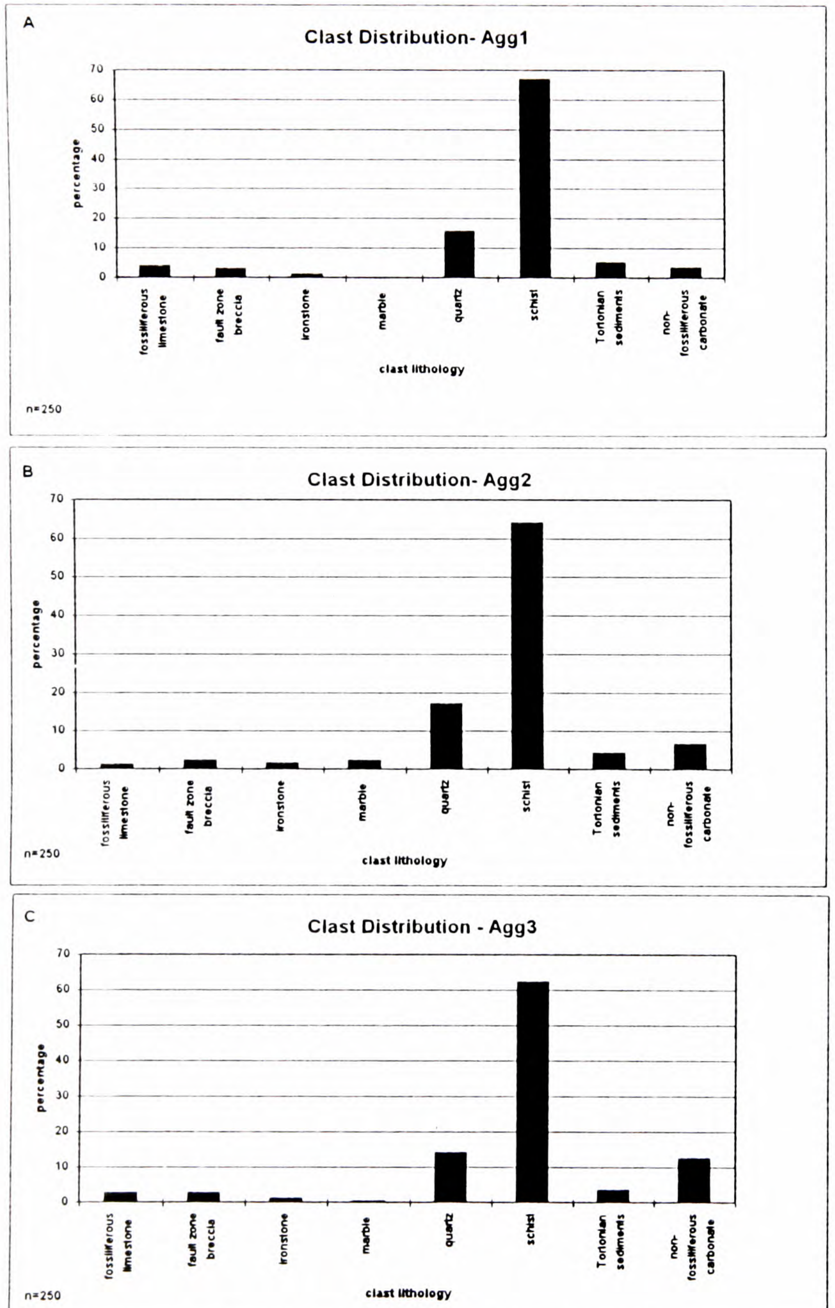


Fig. 4.22 Clast Distribution for Terrace Group 3.

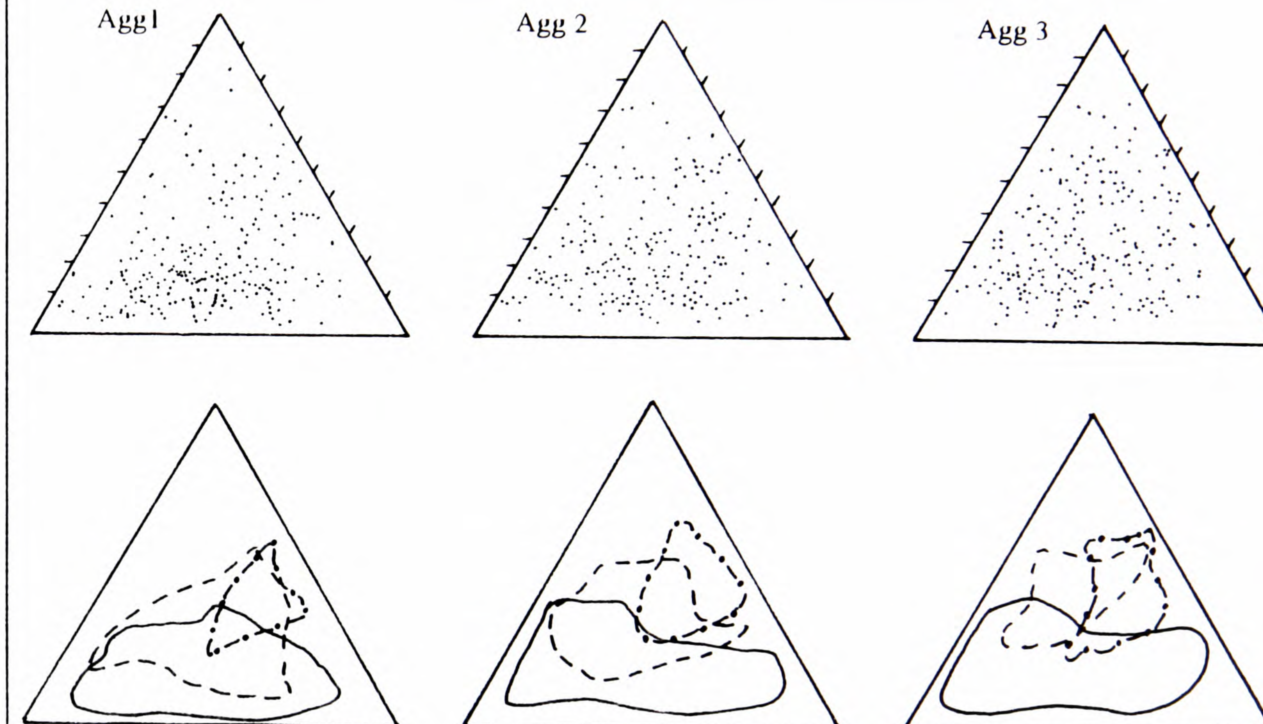
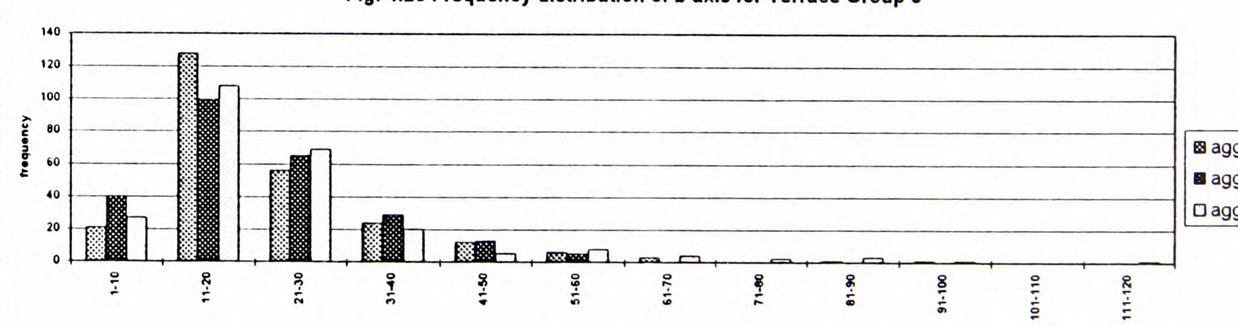


Fig 4.24 Triangular plot of particle shape. Facies envelopes show the shape of the dominant clast lithologies within this terrace level (— = Schist, - - - = Tortonian sediments, -•-• = Triassic clasts).

Fig. 4.23 Frequency distribution of b-axis for Terrace Group 3



Note. for all these diagrams Agg 1-3 are sample sites located on Figure 4 21

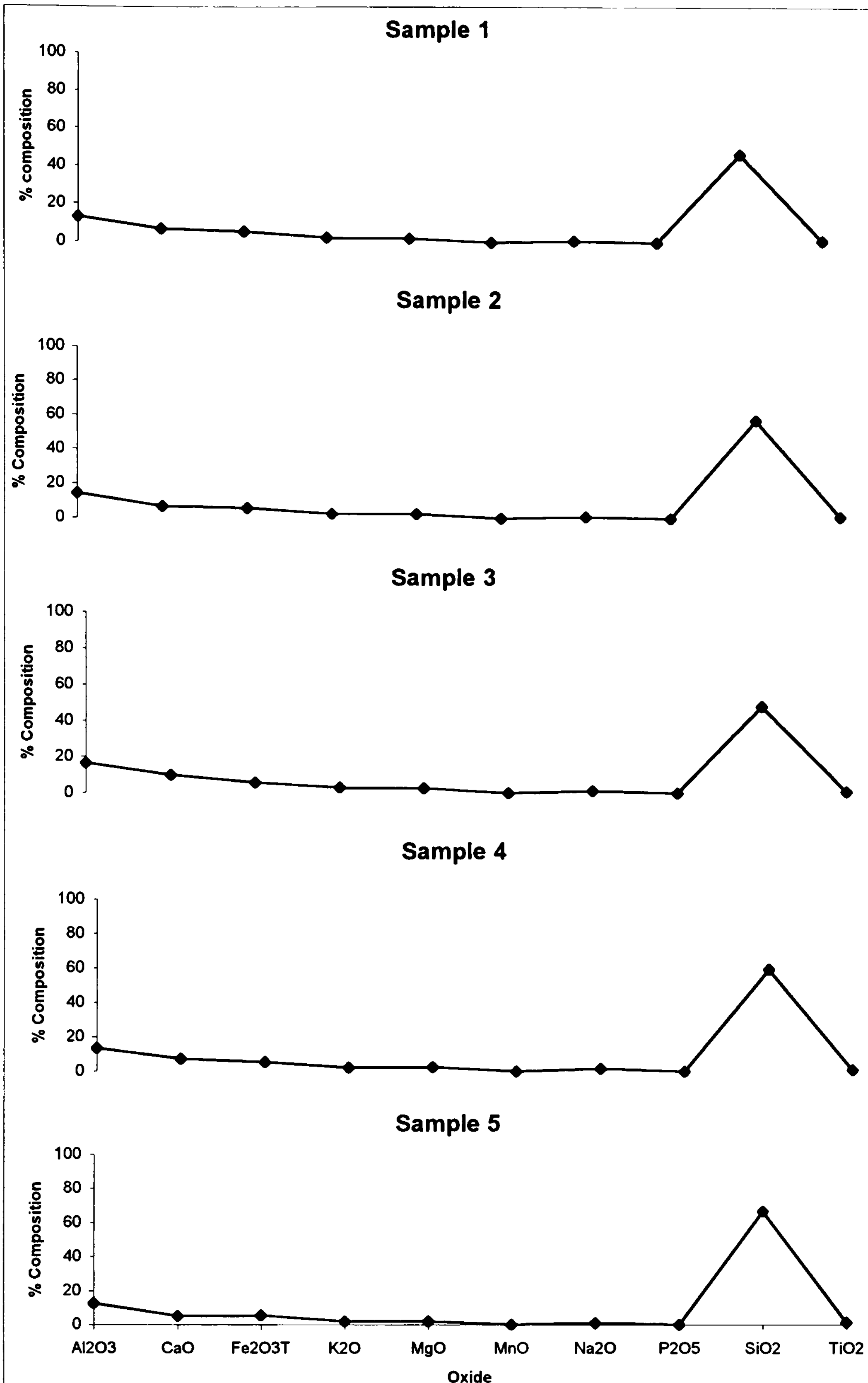


Fig. 4.25A Percentage Composition of common Oxides in Terrace Group 3
(Fe_2O_3T = Total Iron Oxides). Samples 1-5 are located on Figure 4.21

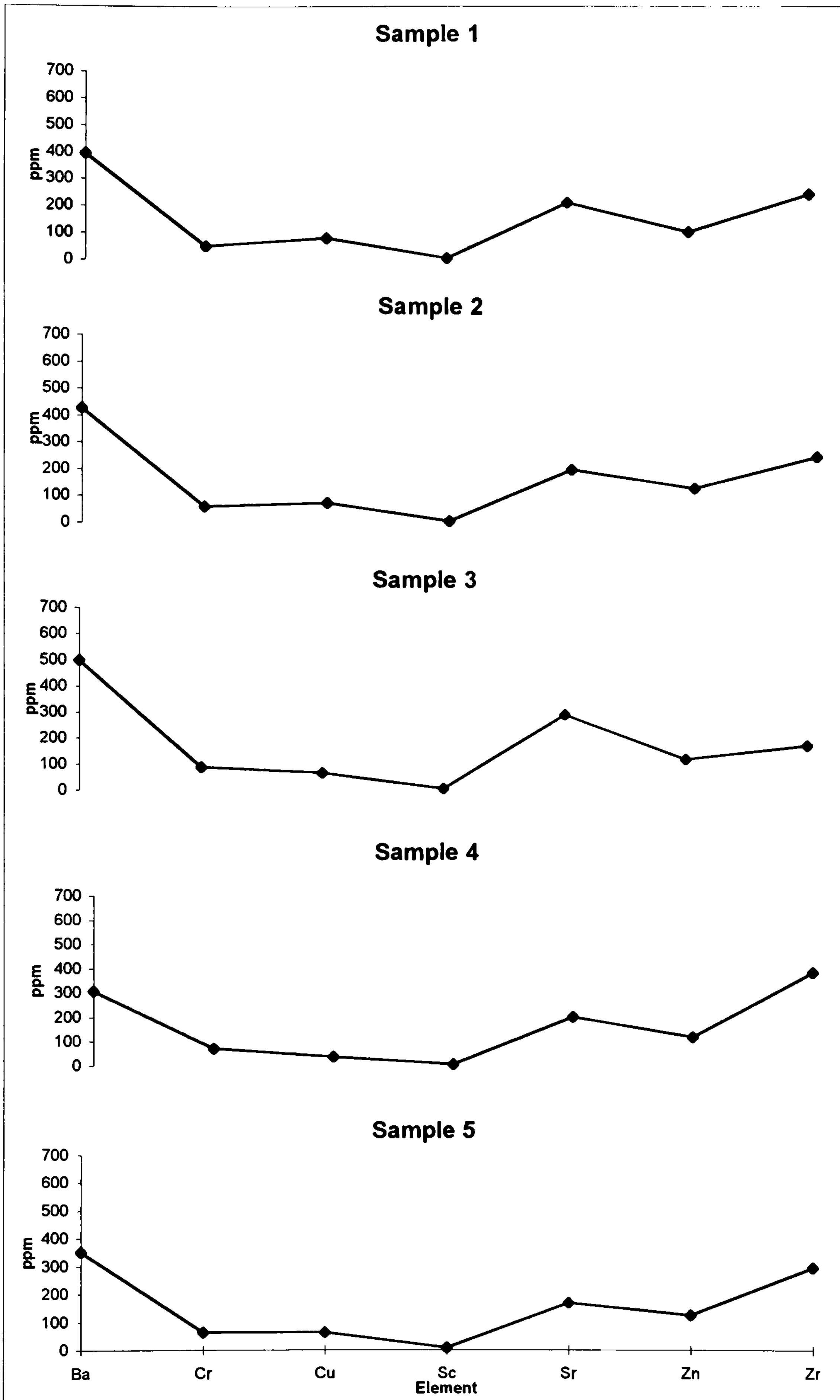


Fig. 4.25B Abundance of Trace Elements in Terrace Group 3
Samples 1-5 are located on Figure 4.21

4.4 TERRACE GROUP 4

4.4.1 Morphology

This generic terrace group forms a unit which reaches a maximum of 10 m in thickness, with its base on the current Lucainena channel. The lateral extent of this terrace is small being exposed for only 200 m (Fig. 4.26).

4.4.2 Sedimentology

This terrace group consists of a layer of orange/brown sands about 6 m in thickness above which there is a consistent coarse gravel/cobble bed 1 to 2 m thick and at the top a thin layer of orange/brown sands 2 to 3 m thick (Fig. 4.26). In contrast to Terrace Group 3 the gravel bed described in this terrace is a consistent band which can be traced across the section. The distinct change between the deposition of fine and coarse sediments indicates a rapid change in the fluvial regime. The gravel bed is clast supported and consists of schist, quartz, fossiliferous limestone, fault zone breccia, non-fossiliferous carbonate clasts and Tortonian/Pliocene sediments. Imbrication was seen in some of the gravel clasts and palaeocurrent measurements were taken which indicated a palaeocurrent direction concurrent with the existing drainage.

Clast counts were taken (n=100) to determine the lithological composition, relative velocity and particle form. As can be seen from Figure 4.27 the dominant lithologies are schist, quartz, fossiliferous limestone and Tortonian\Pliocene sediments. The average Krumbein value is 0.55. The dominant b-axis is between 31 and 40 mm with a maximum of 121 mm and a minimum of 11 mm (Fig. 4.28). The ternary particle form diagrams in Figure 4.29 show a spread of points around the triangle, but with few approaching blocky form. The facies envelopes show some overlap with the schist plotting to the bottom of the diagram exhibiting a slab like form, and the Tortonian/Pliocene sediments and fossiliferous limestone plotting towards the centre right of the diagram, exhibiting an elongate blocky particle form.

4.4.3 Other Distinguishing Features

Geochemical analysis were carried out on samples of fines collected from this terrace group (Fig. 4.30). As with the samples of Terrace Group 3, trace element and oxide data was obtained. The geochemical signature of this terrace group was compared with that of Terrace Group 3. As can be seen from Figure 4.30 similar signatures were found and when average signatures were produced for each terrace group only subtle differences were found (Fig. 4.31). This suggests 3 possibilities: (1) Terrace Groups 3 and 4 are the same, (2) the source areas for both terrace groups are the same; or (3) Terrace Group 4 is made up of reworked material from Terrace Group 3.

Explanation (1) does not appear to be correct because the average height of Terrace Group 4 is 5.2 m, significantly lower than that of Terrace Group 3 which is 16.2 m. The clast assemblages are also different (Fig. 4.22 & Fig. 4.27) although schist is still the dominant clast type, but a greater proportion of fossiliferous limestone, non-fossiliferous carbonate clasts and Tortonian/Pliocene sediments are found in Terrace Group 4. Explanation (2) is likely, although it would be expected that there would be other terrace fragments associated with this terrace deposit further upstream, of which none were identified. Also it would be likely that certain peaks would be emphasised by the input of sediment from further downstream, for example the non-fossiliferous carbonate and Tortonian/Pliocene sediments, which may add greater proportions of strontium, barium and zirconium, subtly altering the geochemical signature. Explanation (3) is also possible because Terrace Group 4 is only found downstream of Terrace Group 3, and Terrace Group 3 was made up of a large proportion of aggradational fines which would have plugged the main channel and eventually would have been washed out. These could quite possibly have built up at some point lower downstream and formed Terrace Group 4. It would also be expected that the geochemical signatures would be similar with reworked material.

The most likely possibility is therefore, that of explanation (3) although explanation (2) is also possible and should not be dismissed. The conflicting morphological and sedimentological data rules out the possibility of explanation (1).

4.4.4 Age Relationships

Terrace Group 4 is identified as the youngest terrace group in the Lucainena catchment. Again two reasons can be given for this, firstly it occurs at the lowest elevation of the four terrace groups identified in the Lucainena catchment; and secondly, the geochemical analysis has suggested that it is made up of reworked sediments from Terrace Group 3.

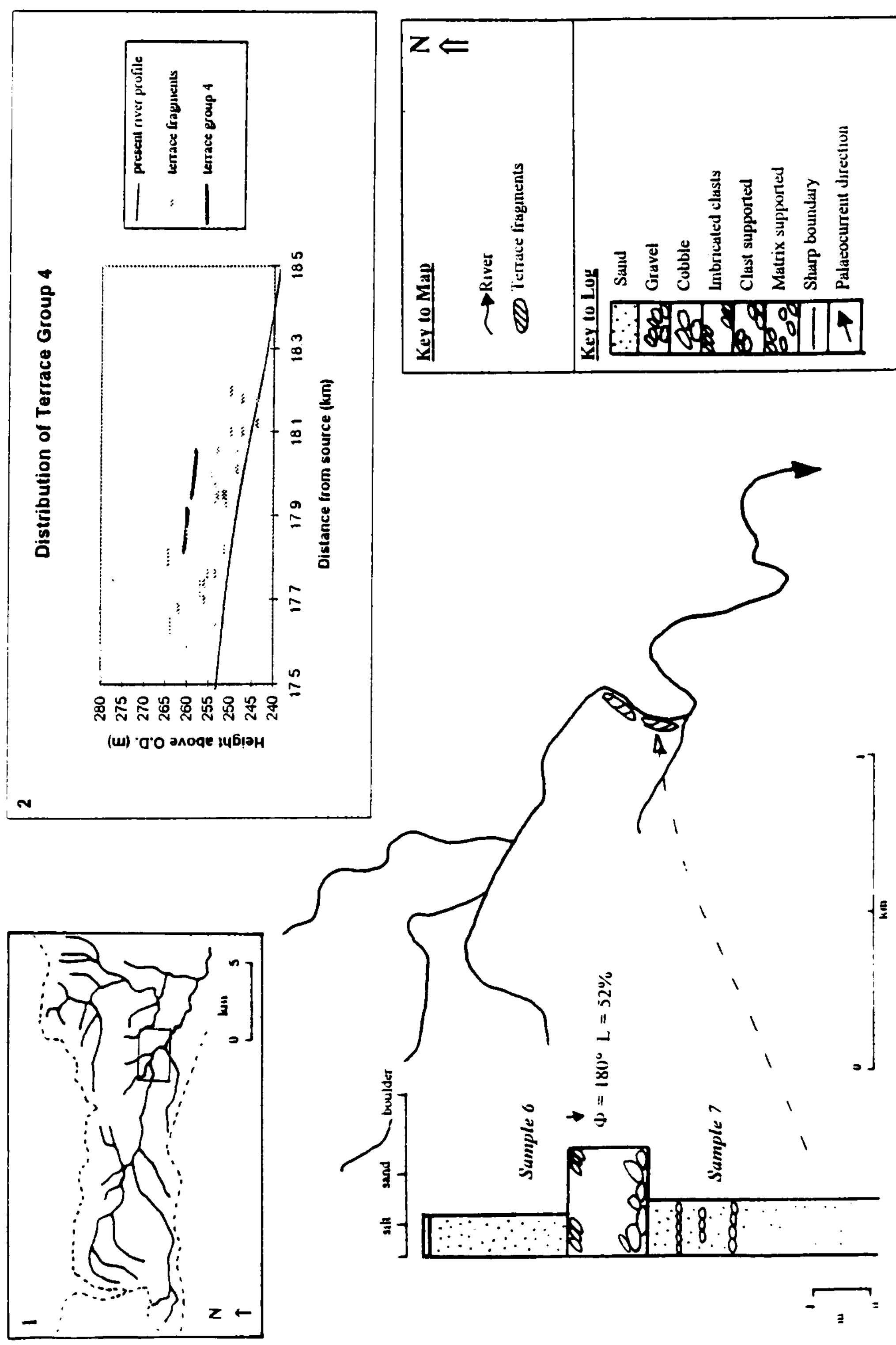


Fig. 4.26 Distribution of Terrace Group 4

Inset 1 shows the location of the main figure
Inset 2 shows the height-distance graph for Terrace Group 4

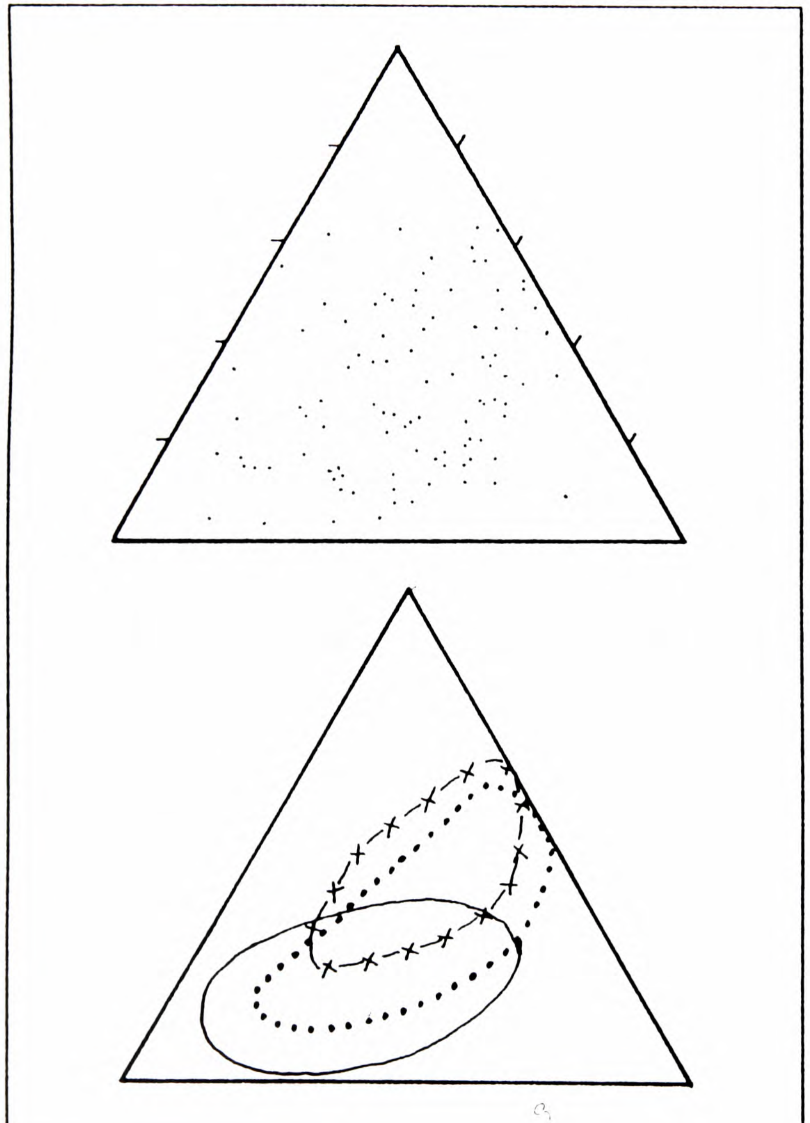


Fig. 4.29 Triangular plot of particle shape for Terrace Group 4. Facies envelopes show the shape of the dominant clast lithologies within this terrace group (• • • • = Tortonian/Pliocene sediments, –x–x–= fossiliferous limestone, ——— = Schist).

Fig. 4.27 Clast distribution for Terrace Group 4

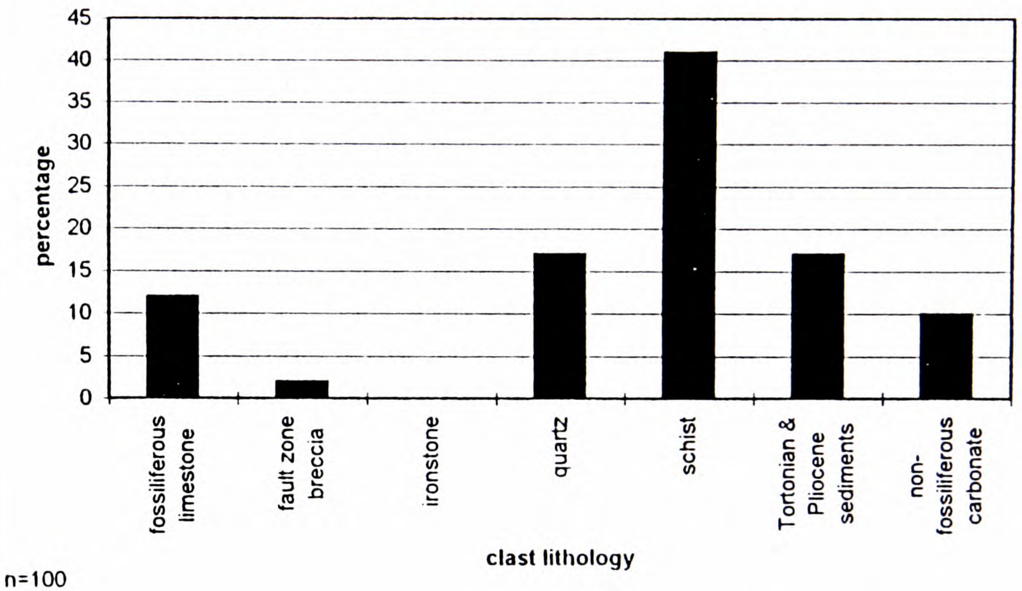
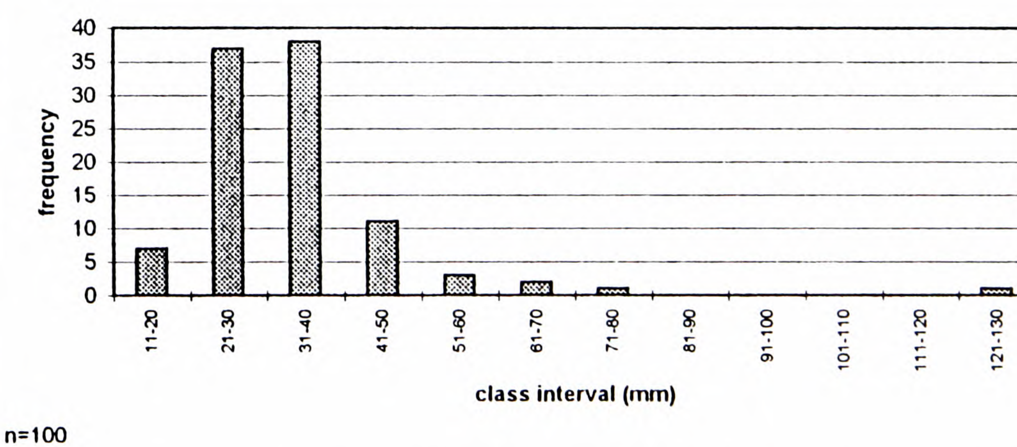


Fig. 4.28 Frequency distribution of b-axis for Terrace Group 4



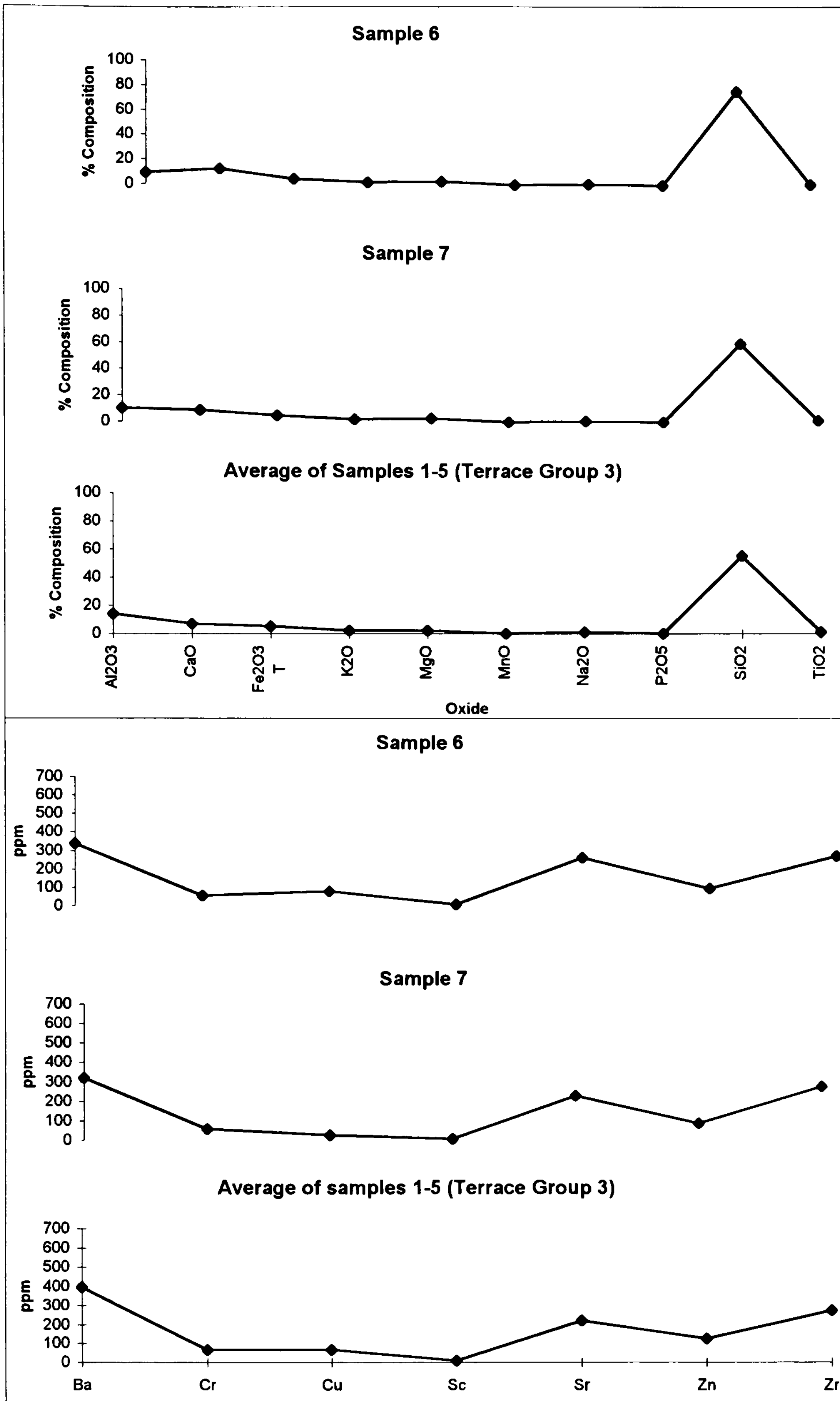


Fig. 4.30 Abundance of Oxides and Trace Elements in Terrace Group 4
Averages of Samples 1-5 are provided to compare geochemical signatures. For sample locations see Figure 4.21 for samples 1-5 and Figure 4.26 for samples 6 & 7.

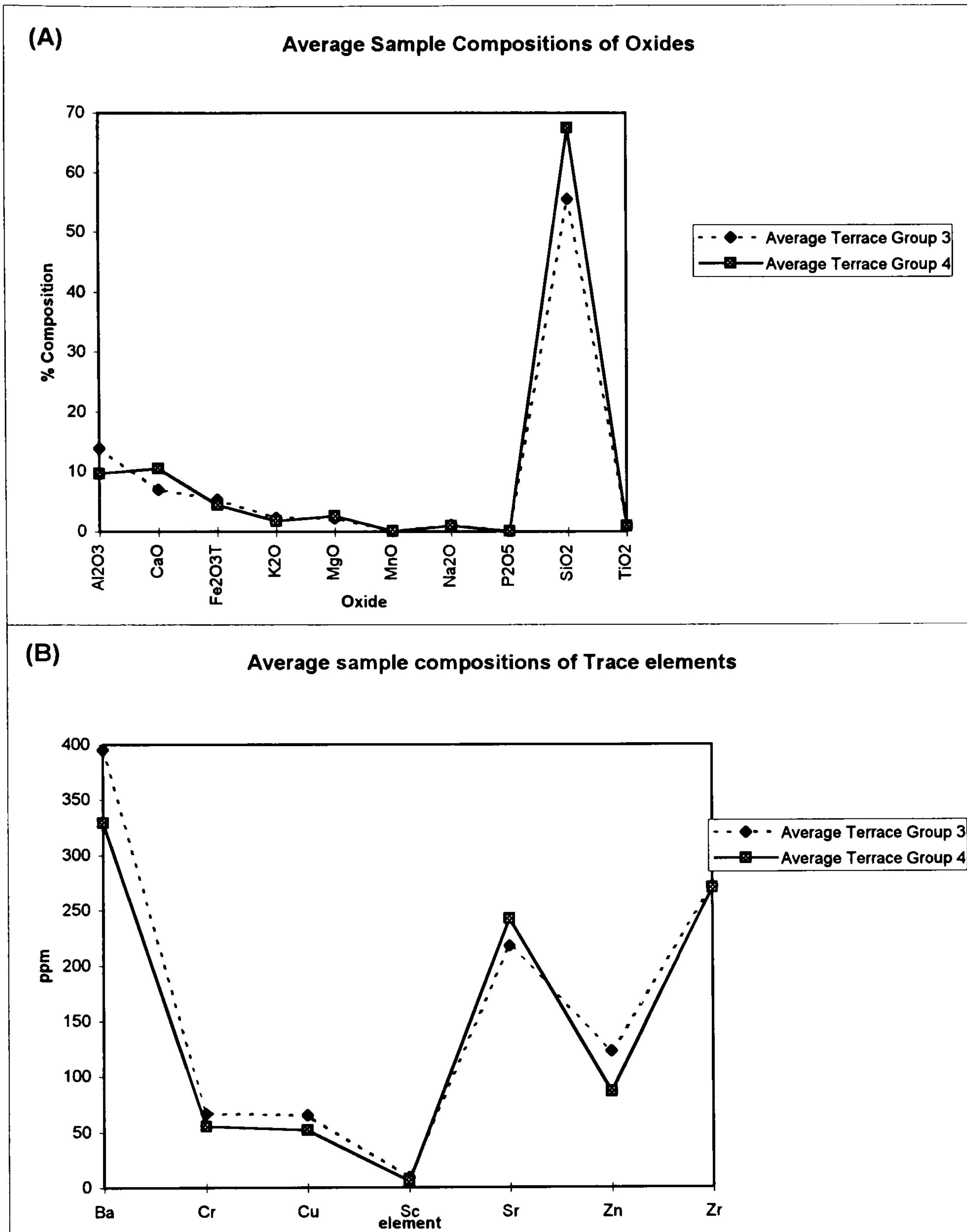


Fig. 4.31 Geochemical signatures produced from Averages of Samples 1-5 (Terrace Group 3) and Samples 7 & 8 (Terrace Group 4). (A) shows average oxide compositions and (B) shows Average trace element compositions.

4.5 SUMMARY

Four key generic terrace groups have been identified within the Lucainena catchment which represent four important episodes in the drainage development of the Rambla de Lucainena. The chronology and palaeoenvironmental significance of these terrace groups will be discussed in the subsequent chapter. Several important characteristics have been recorded within this chapter which will help with these interpretations. These are identified below and will form the basis for discussion in Chapter 5.0.

(1) Each of the four terrace groups is associated with a distinct assemblage of clast lithologies. These cannot be explained solely in terms of the erodability of the different catchment lithologies determined in chapter 3.0. Of particular note is firstly, the low abundance of schist clasts found in Terrace Group 1 relative to the other three terrace groups, where it is a dominant lithology. This is surprising since schist is associated with the highest rates of erosion within the catchment as reported in Chapter 3.0. Consequently the low schist abundance in Terrace Group 1 needs explanation. Secondly, there is a fluctuation between the dominance of schist clasts and clasts of Tortonian sediments in the three facies of Terrace Group 2 which needs explanation. These clast types are sourced from different parts of the catchment and appear to reflect some form of environmental control. Thirdly, the clast assemblage of Terrace Groups 3 and 4 are dominated by schist in excess of that which can be explained by the erodability data for this lithology (Chapter 3.0), which again may be of environmental significance.

(2) The terrace groups exhibit a range of different environmental conditions and depositional facies. Terrace Group 2 appears to exhibit the highest rates of flow as it is associated with debris flow deposits capable of carrying large boulders. This suggests an environment prone to extreme storm events and rapid but short lived sediment transfers. Terrace Group 1 is associated with large b-axis clasts (Table 4.1), but does not contain debris flows suggesting a less extreme climatic regime or a greater degree of storage ability, perhaps associated with more vegetation. Smaller clast sizes were identified in Terrace Groups 3 and 4 indicating less

extreme flow regimes (Table 4.1). However, the facies variations within Terrace Group 3 are suggestive of frequent flooding episodes perhaps associated with more perennial channels. The freshwater ostracods identified within this terrace group are also consistent with temporary water bodies associated with this sort of fluvial regime.

CHARACTERISTIC	**TERRACE GROUP**		
	1	**3**	**4**
most dominant b-axis measurement	41-50 mm	11-20 mm	31-40 mm
largest clast size (b-axis)	140 mm	110 mm	121 mm
Highest flow regime (in Rank order 1= highest)	2	4	3

Table 4.1 Summary table illustrating characteristics used to determine flow regime

(3) Within two of the terrace groups distinctive sedimentary facies have been documented which could yield important palaeoclimatic information. Firstly, within Terrace Group 2 clast fracture and clast pair fracture have been identified. These clast fractures affect a large proportion of the clasts and are indiscriminate of clast lithology or clast size. This is a rarely observed phenomena within terrace fragments and is worthy of further investigation and discussion to attempt to determine the mechanisms of this type of fracturing. Secondly, Terrace Group 2 consists of a distinct aggradation phase dominated by fines.

In addition to these three principal points, which require further discussion in Chapter 5.0, a number of minor points have emerged which are dealt with here and relate to the distribution of terrace fragments, clast lithology and the role of geochemistry.

The best terrace sequences of Terrace Groups 2 and 3 were identified close to major tributary junctions as anticipated in Chapter 3.0. The increased elevation of these terrace remnants close to tributary junctions has also been identified as a limiting factor in determining specific terrace levels, as the height of individual terrace remnants can be influenced locally. This has been a contributing factor to the establishment of generic terrace groups rather than terrace levels.

Lithology has been established as an important factor in determining particle shape. It is the composition of sediments which determine the shape a clast will take, for example, schist clasts were shown to exhibit an elongate to slab shape which is probably heavily influenced by the high proportion of platy mica minerals this lithology contains, Tortonian/Pliocene sediments on the other hand exhibit a more rounded clast shape probably due to their lack of internal structure, and non-fossiliferous carbonate clasts are made up of dense limestones and dolomites which due to their high resistance and structure-less nature result in block shape clasts.

Geochemical analysis in terms of oxide and trace element data has been shown to have potential as a terrace correlating tool and for providing more detail about terrace composition and provenance. However, as was seen from the analysis of fines from Terrace Groups 3 and 4, care must be taken to consider elements such as similar source areas and reworking. More research should be undertaken in this area to develop the potential of such a technique.

5.0 THE DRAINAGE HISTORY OF THE RAMBLA DE LUCAINENA

Four main terrace groups have been identified within the Lucainena catchment as documented in Chapter 4.0. These terrace groups represent major episodes in the drainage history of the Rambla de Lucainena. It is the purpose of this chapter to develop a relative chronology of the sequence of events occurring in this catchment and where possible suggest the role of climate and tectonics in them. Each episode will be described as a stage in the history of the drainage development of the Rambla de Lucainena.

Five key stages have been identified from the evidence documented in Chapter 4.0 and these are summarised below. Each of these stages will be looked at in more detail in the remainder of the chapter.

The first stage in the drainage history of the Rambla de Lucainena is Stage A. This stage records the deposition of Terrace Group 1 and its abandonment due to uplift and incision (Fig. 5.1). Stage A is then followed by Stage B, the deposition of Terrace Group 2 (Fig. 5.1). There was no evidence of base-level change or incision after the deposition of this terrace group. Stage C (Fig. 5.1) documents the aggradation of the thick deposits of fines of Terrace Group 3. The deposition of this terrace group completely buries Terrace Group 2. A period of incision and erosion cuts through both Terrace Groups 3 and 4, and results in the deposition of a lower reworked terrace group, Terrace group 4. This is referred to as Stage D in the drainage history (Fig. 5.1). Stage E documents the subsequent incision and deposition of a selection of lower terrace fragments.

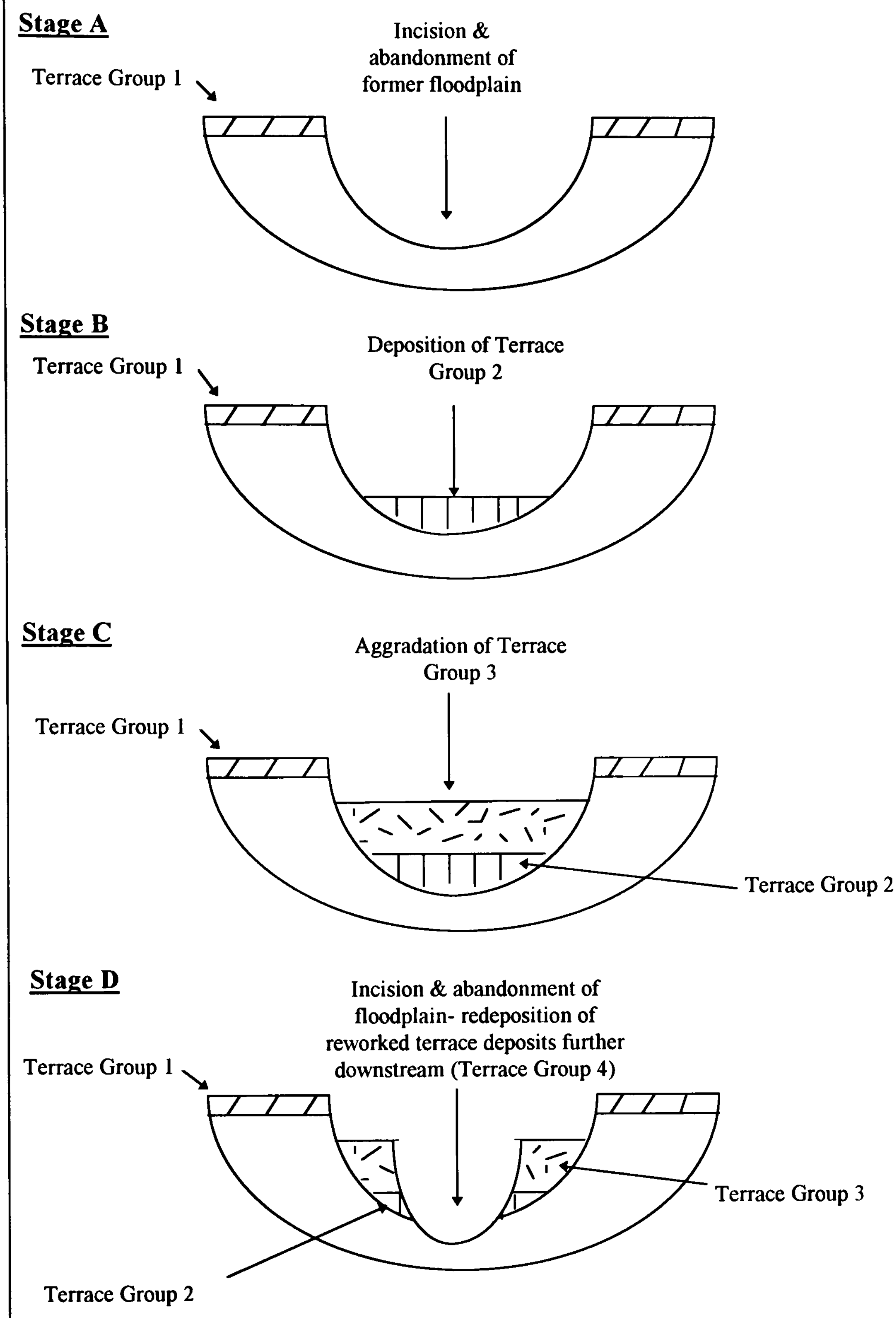


Fig. 5.1 Schematic diagrams to represent Stages A-D in the drainage evolution of the Rambla de Lucainena.

5.1 STAGE A

The oldest terrace group to be identified within the Lucainena catchment is Terrace Group 1 (Fig. 5.1). This terrace group occurs at high levels and can be traced over a large distance. The maximum clast sizes, sedimentological characteristics (i.e. absence of debris flows and sediment bars) and thickness of this terrace group suggest that it was not deposited in response to a large scale single event within the catchment, but probably represents smaller scale deposition over a longer time period. The main characteristic of this terrace level is its low levels of schist clasts which are a dominant clast type of the majority of terrace fragments within the Lucainena catchment. The largest source area for schist deposits is the Rambla Honda tributary junction (Fig. 1.5). Small outcrops of schist are also seen in the main channel of the Rambla de Lucainena around this junction, and reworked clasts are found within Tortonian and Pliocene sediments.

The low levels of schist within this terrace group therefore suggests 3 possibilities:
(1) The Rambla Honda previously drained south to north into the Sorbas basin and was not captured at the time this terrace group was deposited (Fig. 5.2A).
(2) That there was a significant climatic event in the headwaters of the Rambla de Lucainena at the time of deposition of Terrace Group 1 which did not affect the Rambla Honda tributary (Fig. 5.2B), and that the sediments of this terrace group were deposited during this single event.
(3) The Rambla Honda was captured at this time, but only drained a small catchment and input small volumes of schist debris into the main channel. Because higher levels of schist are found in other terrace groups it could be assumed that after the deposition of this terrace group, a period of incision and erosion opened up the catchment of the Rambla Honda until it reached its present size, and this provided a larger supply of schist debris to all terrace groups older than Terrace Group 1 (Fig. 5.2C).

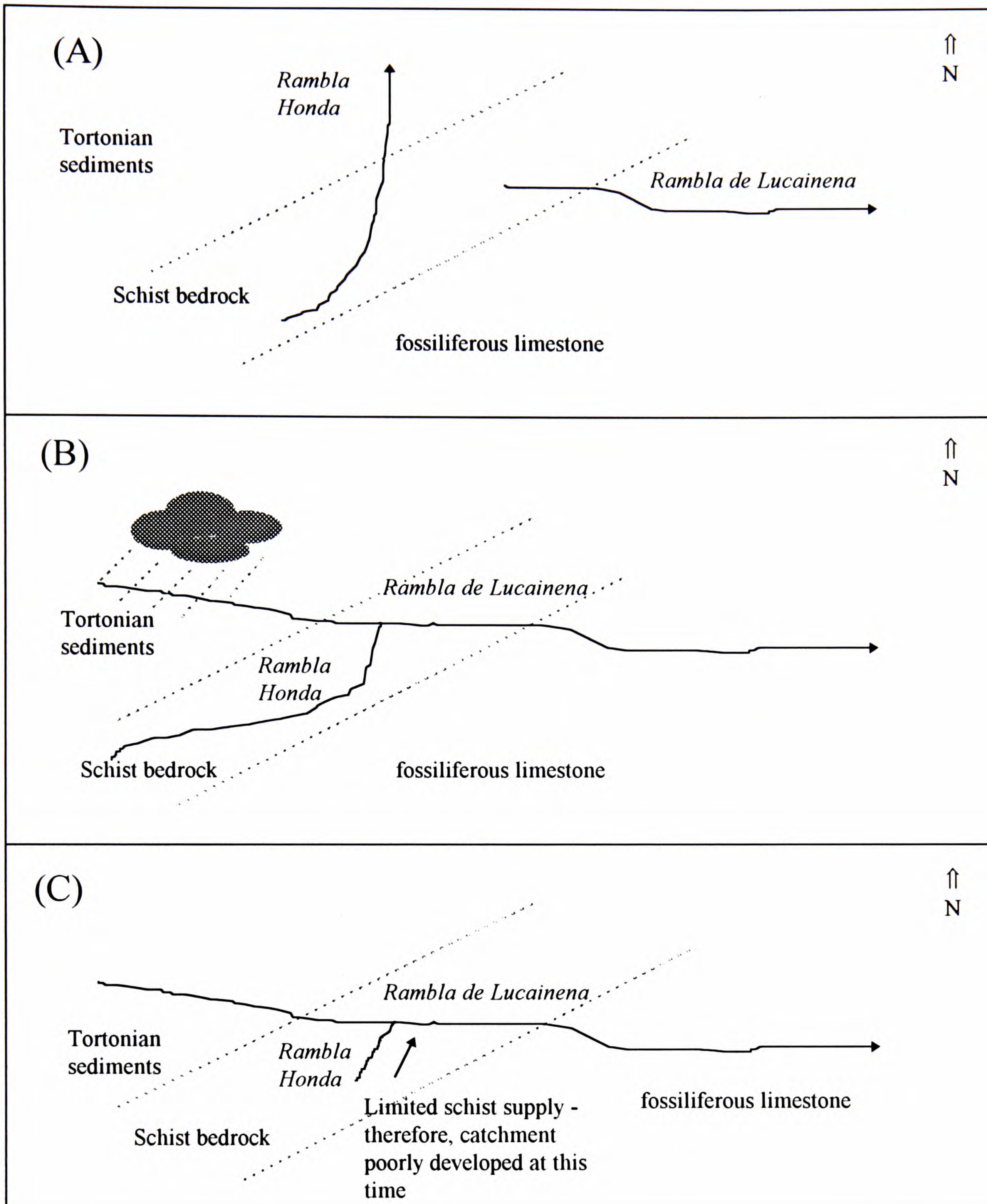


Fig. 5.2 Schematic diagrams representing the possible drainage pattern of the Rambla de Lucainena at the time of deposition of Terrace Group 1. (A) Suggests the Rambla Honda was not captured at this time and formed one of pre-existing S-N channels draining into the Sorbas Basin as described by Mather & Harvey (1995). (B) Suggests that the Rambla Honda had been captured at this time but that the deposition of Terrace Group 1 was associated with a major climatic event in the head waters of the Rambla de Lucainena. (C) Suggests that the Rambla Honda was captured but poorly developed and so provided only a limited schist supply at this time.

Hypothesis (2) can be dismissed because the sediment of this terrace is not consistent with rapid sedimentation but with gradual fluvial sedimentation, and there is no obvious climatic reason for a recurrence of rainfall events in just one part of the catchment. Similar problems exist with hypothesis (3) as the subsequent incision and erosion of the Rambla Honda catchment required to dramatically increase its size relative to the rest of the system, after the deposition of Terrace Group 1, would require some form of stimuli, such as a concentration of rainfall in the catchment or a tectonic event. There is no evidence for either. Therefore, the most likely explanation is that of the first hypothesis because this ties in with descriptions of the pre-existing drainage patterns and drainage capture of the Rambla de Lucainena during the pre to early Quaternary (Mather, 1993a; Mather & Harvey, 1995). The Rambla Honda was probably a south to north drainage system flowing into the Sorbas Basin at the time of deposition of Terrace Group 1. Thus, the Rambla de Lucainena would have headcut only a small way into the schists at this time and provide a very limited supply of schist debris to the catchment. Subsequent to the deposition of Terrace Group 1, the Rambla Honda would have been beheaded and captured like many rivers in this area, by the aggressive headcutting of the Rambla de Lucainena, therefore, increasing the schist supply to the catchment.

5.2 STAGE B

Following the deposition of Terrace Group 1 there was a period of uplift and incision followed by the deposition of a lower terrace group, Terrace Group 2 (Fig. 5.1). This terrace group forms a cemented deposit and consists of three different conglomerate facies. These facies have been described as debris flow deposits (section 4.2.2) and 40-70 % of each deposit is matrix supported. This terrace group is unlike others identified with the Lucainena catchment, as others were dominantly clast supported, this suggests that this terrace was deposited more rapidly and was probably associated with an extreme climatic event. Due to the fact that the largest clast sizes were identified within this group it is more likely that this terrace was deposited due to rapid accretion during a single event or a series of closely spaced episodes, unlike Terrace Group 1.

The key properties of this terrace group are the different clast assemblages represented within each facies and the presence of fractured clasts which are discussed below.

5.2.1 Clast Assemblages

Each conglomerate facies has a different clast distribution (Fig. 4.10) indicating a different provenance. Facies A shows a dominance of Tortonian sediments, Facies B a dominance of schist clasts and Facies C more equal proportions of both Tortonian sediments and schist clasts. The Tortonian sediments and schist clasts are sourced from two different parts of the catchment (Fig. 5.3).

Several explanations for these changes in clast distribution can be suggested:

(1) The clast distribution for Facies A may suggest a major climatic event isolated to the headwaters of the Rambla de Lucainena, providing a dominant clast assemblage of Tortonian sediments (Fig. 5.4A), whilst Facies B may reflect a climatic event isolated in the headwaters of the Rambla Honda, providing a dominant assemblage of schist clasts (Fig. 5.4B).

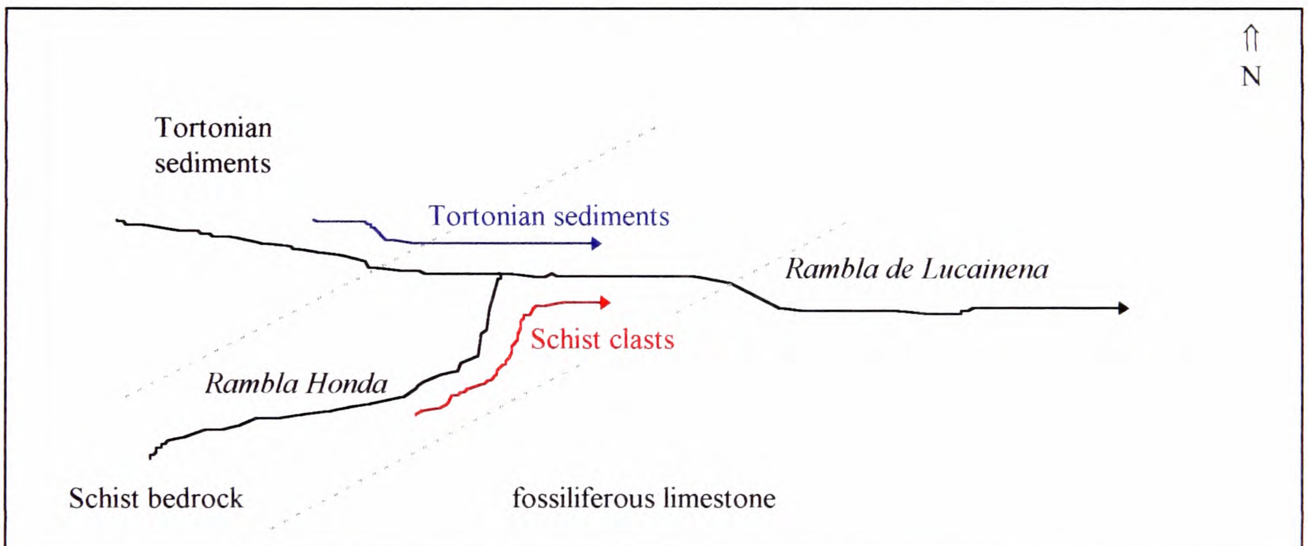


Fig. 5.3 Schematic representation of provenance of schist clasts and Tortonian sediments near the Rambla Honda tributary intersection.

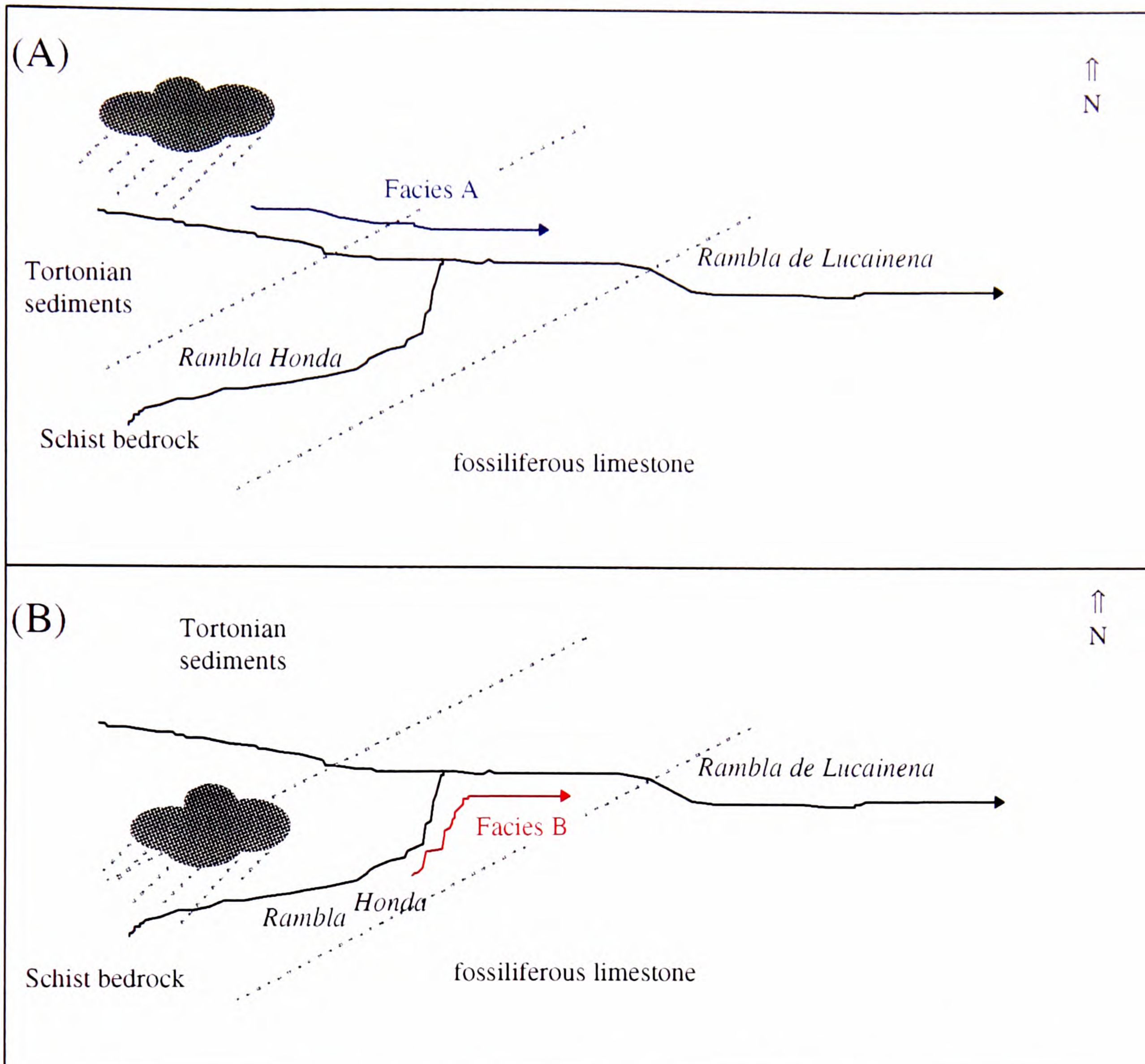


Fig. 5.4 Schematic diagram representing climatic variations in different parts of the catchment. (A) Suggests the deposition of Facies A associated with heavy rainfall isolated to the upstream catchment of the Rambla de Lucainena. (B) Suggests the deposition of Facies B associated with heavy rainfall isolated to the upstream catchment of the Rambla Honda.

(2) The rapid change of clast types between one facies and the next may reflect the storage capacity of different parts of the catchment. As identified in section 3.2, the erosion rates of a certain lithology and the storage capacity of a catchment, control the input of bedload sediment into a channel. It was also found that the erosion rates of weathered schist regolith were higher than that of weathered Tortonian regolith, and that the schist catchment afforded very little storage of bedload within it's narrow channels and that the Tortonian catchment with its wider channels stored much greater amounts of bedload. Therefore, if a storm event occurred across the catchment it could be expected that the initial input of sediment would come from stored sediment of which the greatest amount would be found in

the Tortonian catchment. This would provide an initial clast assemblage dominated by a wave of Tortonian sediments as exhibited in Facies A (Fig. 5.5A). Once this stored material had been flushed out of the catchment any further sediment input would come from erosion. As the schist regolith erodes at a greater rate than the Tortonian regolith, then at this point the Tortonian clast dominance would be replaced by schist clasts, as shown in Facies B (Fig. 5.5B). Facies C shows a mixed clast assemblage and would represent the point where some channel stores have built up again in the Tortonian catchment and the input from these stored sediments is keeping pace with the input from eroded sediments (Fig. 5.5C).

(3) Facies B could reflect the sudden influx of material from the Rambla Honda associated with an avalanche, undercutting of a channel or sudden headcut. An event such as this would input a large amount of schist debris rapidly into the catchment causing a dominance of schist clasts as seen in Facies B.

All of these explanations are plausible. Hypothesis (1) requires significant rainfall events located only to certain parts of the catchment which due to the localised nature of rainfall in semi-arid areas such as this, is possible, providing that each facies within this terrace group was deposited during a single climatic event. However, sedimentological evidence, such as gradational boundaries between facies and some facies mixing, suggests that there was little or no time between the deposition of each facies, indicating that each facies must have been deposited by closely spaced climatic events. Hypothesis (2) reflects the storage capacities within different parts of the catchment identified in section 3.2 and fits with the higher erosion rates of the schist regolith and greater channel storage capacity of the Tortonian sediments. Hypothesis (3) is also possible but is difficult to prove or disprove. Therefore, the cause of these facies fluctuations is unknown but appears to be most readily explained by hypothesis (2).

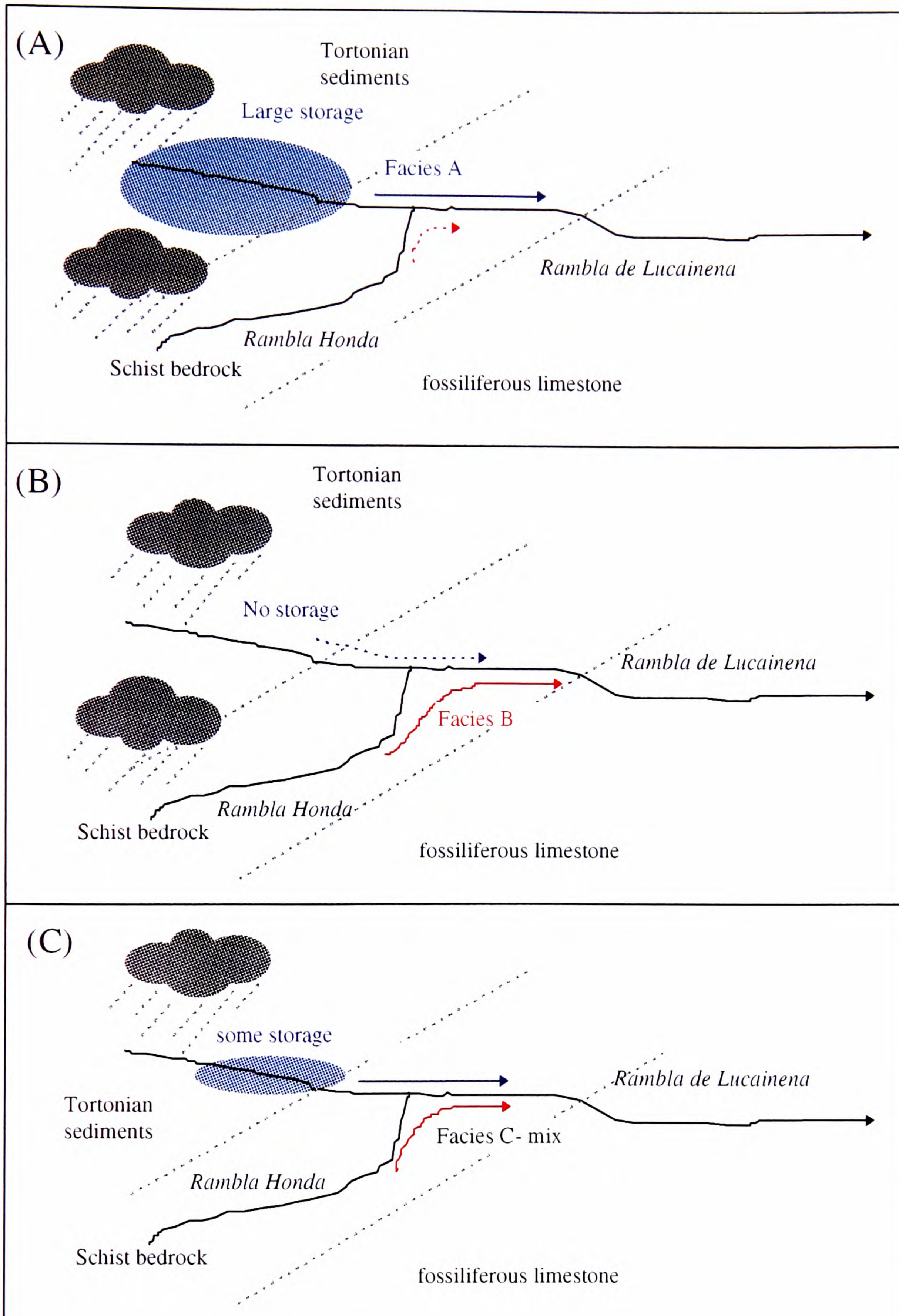


Fig. 5.5 Schematic diagrams to represent how storage may have influenced the clast assemblage of facies in Terrace Group 2. (A) represents the deposition of Facies A due mainly to washout of stored sediment in the headwaters of the Rambla de Lucainena (B) represents the deposition of Facies B as the Tortonian catchment has been wiped clean of stored sediment. (C) represents the deposition of Facies C where small amounts of sediment have built up in the headwaters of the Lucainena catchment and are mixed with schist clasts sourced from the Rambla Honda. ——▸ dominant bedload input ·······▸ minor bedload input

5.2.2 Fractured Clasts

One of the most interesting and intriguing features of this terrace group was the presence of fractured clasts within these facies, documented in section 4.2.3. Clast fracture is found in greater than 50% of the clasts within one facies and the fracturing is indiscriminate of clast lithology. As some of the fractured clasts are infilled with matrix there was a possibility that the deposition of the clasts and the matrix was a two stage process, however, as the matrix is of an even consistency throughout each of the facies and shows no differentiation it is likely that the matrix was deposited contemporaneously with the clasts. The clast fracturing is not pervasive into the matrix of any of the facies which suggests the clasts were fractured before cementation of the matrix. Several possible mechanisms of clast fracture have been documented in the literature which are appropriate to tectonically active semi-arid areas: (1) Tectonics (Pickering, 1983; Pickering, 1984); (2) Weathering (Cooke & Smalley, 1968; Peterson, 1980; Sperling & Cooke, 1985; Blikra & Longva; 1994); and (3) Debris flow processes (Ui *et al.*, 1986; Ballance & Gregory, 1991; Palmer *et al.*, 1991; Smith & Lowe, 1991). Each of these possibilities are discussed below:

Tectonics

The Rambla de Lucainena catchment is situated within a region which is known to be tectonically active (Mather, 1993a; Harvey & Wells, 1987 and Weijermars *et al.*, 1985). Clast fracture could be initiated either by faulting or liquefaction caused by earth tremors. Faulting could split the clasts along the fault zone during displacement. Alternatively, earth tremors initiated by tectonic movements could liquefy cohesive sediments, effectively allowing clasts to move within the matrix. Where clasts are in contact or come into contact the transmission of shear stresses through the clasts may be sufficient to cause clast fracture. Liquefaction may also allow the rapid flow of matrix between fractured clasts perhaps helping to propagate the fractures. More importantly since this mechanism assumes that this terrace group had already been deposited prior to this tectonic event, fracture displacement would be minimal because the debris flow deposits would no longer be flowing. The degree of liquefaction and the magnitude of intra-clast contacts should decrease away from the epicentre of the earth tremor and therefore some grading in the occurrence of fractured clasts should be visible. The Northern Boundary Fault may provide the possible tectonic influence required for this type of mechanism as it runs within 2 km of the main site of fracture (Fig. 1.5).

Although plausible this mechanism has a number of difficulties:

(1) There should be other evidence of liquefaction structures preserved within the deposits (Mather & Westhead, 1993). However, no such structures were observed. If faulting were the mechanism and had occurred after deposition then it would be expected that the fractures would also be pervasive into the matrix, which they were not.

(2) The clasts and clast fractures were randomly orientated and didn't reflect any sense of shear which is normally associated with a fault zone.

(3) The dynamics of this stress/shear should decrease away from the epicentre, probably in concentric zones, as found with other evidence of palaeo-seismic activity (e.g. Davenport & Ringrose, 1985). In the case of these deposits a centre of clast fracture is found, but there is no evidence of decreasing zones of clast fracture away from this point. More significantly, there are fragments of this terrace group that are found closer to the Northern Boundary Fault Zone than the main concentration of fractured clast pairs at the Rambla Honda tributary junction, but they do not show increasing fracture density.

(4) Investigation of an out-basin terrace in the Sorbas basin, the B terrace (Harvey & Wells, 1987) which is known to be affected by a fault and along which displacement is seen, showed no such fracturing even close to its fault zone.

(5) No fault was observed in the vicinity of the Rambla Honda tributary junction, the main site of clast fracture.

Weathering

The possible weathering mechanisms suitable for a semi-arid environment are freeze-thaw and salt weathering, both of which rely on the porosity and weaknesses of their host rock (McGreevy, 1981; Smith & McGreevy, 1983). Water can seep into the microcracks and pores of the clasts, and salt crystallisation (Cooke & Smalley, 1968; Peterson, 1980) or freezing of the water increases the volume of the water and exerts pressure on the pores or cracks of the clast which can cause the rock to fracture or disintegrate, especially if this process is continually repeated. There has been much experimentation to simulate the process of salt weathering (e.g. Sperling & Cooke, 1985; Cooke, 1979), and to investigate its effects on rock specimens of varying type (Goudie, 1970) and shape (Robinson & Williams, 1969). Overall the work has suggested that fracture and disintegration vary closely with rock type and that porous lithologies are more prone to fracture by this mechanism. However, some workers have found no evidence for this preference (e.g. Keeble, 1971). The fracturing of clasts in the deposits of this terrace group has shown no preference for clast lithology or porosity.

Although this mechanism is plausible there are several problems with it which are addressed below:

(1) The greatest number of clast fractures are seen in the matrix rich facies of this terrace group and little of the experimental work concerned with freeze-thaw and salt weathering has concentrated on clasts surrounded by a matrix, most deal with sub-aerial or sub-aqueous exposure, which although indicative cannot be directly related to the fractures found here.

(2) Usually this type of process is exploitative of existing weaknesses in rocks and clasts. However, the fracture here seems to be independent of these pre-existing weaknesses.

(3) One of the main problems with a frost shattering mechanism is that it requires sufficiently low average annual temperatures, ideally around -5 to -15 degrees Celsius, however, even at 0°C, frost shattering is possible providing there are a sufficient number of freezing cycles (Blikra & Longva, 1995). The possible

palaeoclimatological implications of this are that annual temperatures in this region may have been close to zero during some periods of the Quaternary, which is previously undocumented.

Debris Flow Processes

Clast fracturing has been recorded within debris flow deposits, and is usually associated with large scale events such as volcanic debris avalanches (Ui *et al.*, 1986; Ballance & Gregory; 1991; Palmer, Alloway & Neall, 1991; Smith & Lowe, 1991). Volcanic debris flows differ from those of other areas in the fact that they are commonly clay poor deposits (Fisher & Schimincke, 1984; Smith 1986) and are larger scale. In other respects the morphology and characteristics of volcanic debris flow deposits are similar to those initiated by any other mechanism (Smith & Lowe, 1991). Brecciated or fractured clasts are common in volcanic debris flow deposits and may be caused by dilation at the time of failure (Glicken, 1991) and then compressional stresses during the period of flowage when clasts are colliding with each other or against the ground surface. With further dilation the clasts may disintegrate along the fractures and fractures become separated by the matrix. Another debris flow environment in which clast fracture has been observed is that of re-sedimented glacial deposits described by Harker (1993). He found that fractures were often associated with point contacts, which is seen in this terrace group, and observed that wider cracks were also infilled with matrix. He surmised that the fractures were caused by the forceful nesting of larger clasts. However, Harker (1993) found that some of the fractures also ran through the matrix and that the fractures were dependant on clast size, neither of which were apparent in Terrace Group 2.

This clast fracture mechanism appears to be possible, but is again subject to several problems:

(1) Clast fracture was most abundant in the matrix supported facies where clast to clast contacts would be minimal due to the buoyant effect of the matrix.

(2) The literature suggests that clast fracturing has occurred through large boulders hitting much smaller clasts, where as the clasts within this terrace group are much more uniform in size.

(3) Within a debris flow deposit the clasts are constantly on the move, therefore it would be expected that a greater degree of displacement between the fractured pieces of clast would be observed. However, identification of clast fragments over large distances is difficult as edges and corners can become abraded.

Clast Fracture Mechanism

The tectonic mechanism of clast fracture although plausible seems unsuitable in this instance. This is due to the lack of obvious liquefaction structures and the fact that the epicentre of clast fracture is not found closest to the Northern Boundary Fault Zone, which is the only apparent site of tectonic activity in this area. Furthermore, clast fracturing of this type is not found at an analogous site in the Sorbas Basin.

The main arguments against the debris flow mechanisms are the fact that the clasts in these facies are generally small scale in comparison to those documented in the literature and are much more uniform in size suggesting that compressional stress transfer would be insufficient to cause such large scale clast fracture. The other key problem is that with a flowing material it would be expected that the clast fragments would be displaced to much greater distance than was apparent within the deposits of this terrace group. Therefore, despite the plausibility of this mechanism, it is unsuitable in this instance.

The most likely mechanism appears to be that of the weathering mechanism and due to the absence of observations of pore water crystal growth, a freeze-thaw rather than salt weathering mechanism is most likely. According to more recent workers such as Blikra and Longva (1995) frost shattering in the field has been found to be more abundant in matrix rich facies than clast supported facies and as the suggested mechanism of deposition for this terrace group is a debris flow, it is likely that during flow the clasts may bump into each or against the river bed, causing small cracks and fractures to be developed within the clasts which could be exploited later by this mechanism. The only real problem with fracture by a freeze thaw mechanism is that frost shattering requires oscillations of temperature close to 0°C. This suggestion may not be as far fetched as it seems as periglacial deposits have been identified in the Subbeitic mountains of the Cordoba Province of southern Spain (Torres-Giron & Recio-Espejo, 1997). Torres-Giron and Recio-Espejo (1997) found these deposits at heights of 1000 m above sea level and suggest that they are just over 80 000 years old. Despite the fact that Terrace Group 2 was deposited at heights of only 350 m above sea level, the finding of these periglacial deposits within the Quaternary in relatively close proximity suggests that sufficiently low temperatures to cause frost clast fracture may have been possible. This has implications for the palaeoclimate in this area at this time suggesting regular temperature oscillations close to 0° Celsius, which is previously undocumented. This conclusion is therefore tentative and requires further exploration into similar climatic settings in SE Spain.

5.3 STAGE C

Terrace Group 2 was buried by the large volumes of fine sands and gravels of Terrace Group 3. Therefore, the next stage in the drainage history of the Rambla de Lucainena is a period of intense aggradation resulting in the formation of Terrace Group 3. This terrace group forms a large expanse of thick sediments in an open area just above a narrow constricting gorge section. There are several characteristics of this terrace group that are worthy of further investigation, firstly that this terrace group cannot be traced below the narrow constricting gorge. Secondly, what the causes of this intense period of aggradation are and its climatic implications; and thirdly, that schist clasts are the dominant clast type of this terrace group and are found in greater levels than can be readily explained by the higher erosion rates discussed in section 3.2.

5.3.1 Distribution of Terrace Group 3

The large build up of fines behind the gorge and the fact that the terrace group cannot be traced below it suggests that the gorge provided a natural check dam through which only small amounts of sediment could pass. This damming could be a result of the narrowness of the gorge itself which did not allow sediment to be removed at the same rate as it was being built up or could be the result of some temporary blockage such as a rockfall or earth avalanche. As there is no visible evidence for the latter explanation, such as scars in the bedrock, the first explanation can be assumed. Freshwater ostracods were also identified within this terrace level which suggest a palaeoenvironment consistent with temporary water bodies which also supports this natural checkdam theory.

5.3.2 Mechanisms of aggradation and palaeoclimatic significance

The sedimentological evidence of this terrace group suggests that it was deposited rapidly due to small scale flooding events, perhaps as overbank deposits. There appears to have been greater channel stability, with a concentration of coarse gravels within them, giving rapid facies shifts from gravels to fines. This would imply a more perennial fluvial system, a consequence of increasing precipitation. This could be associated with increased vegetation cover, although this would reduce sediment availability and consequently the rate of aggradation. An alternative is that temperatures were low, and therefore vegetation cover was low, and consequently more sediment would have been available. At present there is no evidence about temperature and vegetation cover with which to further this argument and further work is needed.

The occurrence of these aggradational terraces immediately above the channel restriction imposed by the gorge is significant, since this is a classic location for flooding (Schumm, 1977). The decrease in channel and floodplain width in the gorge effectively ponds water above it during a storm event. This type of environment appears to be consistent with the observations of ostracods within this terrace group, which are indicative of temporary water bodies and typical of floodplains prone to frequent inundation.

Periods of alluvial aggradation in SE Spain during the Quaternary have generally been attributed to dry glacial climatic phases (Amor & Florschutz, 1964; Harvey, 1984; Harvey & Wells, 1987). However, the observations here suggest that aggradation may also be associated with pluvial periods and provide a contrasting style of aggradation. More importantly it indicates a more complex link between climate and environmental response than is frequently assumed in this region.

5.3.3 Clast distribution

Schists were dominant in the gravels of this terrace group occurring at much higher levels than any other clast type. Despite the higher erosion rates determined for the schist regolith, the schists clasts occur in greater abundance than might be expected. The high levels of schist within this terrace group may suggest that:
(1) The Rambla Honda was inputting large volumes of sediment into the catchment at the time of deposition of this terrace group, perhaps due to rapid headcutting and slope undercutting, inducing mass failure and the accumulation of abundant debris in the channel floor.
(2) That the rates of erodability are accentuated in a wetter climate perhaps due to greater chemical weathering.

The first hypothesis is unlikely as it would require a tectonic event restricted to only one part of the catchment. The second hypothesis is the most likely as the sedimentological evidence for this terrace group suggests that the climate was much wetter than that of today. This means that the erosion rates calculated for the current semi-arid climate, in chapter 3.0, are likely to be exaggerated and a greater proportion of schist relative to the other sediments could be expected.

5.4 STAGES D & E

Following the deposition of Terrace Group 3 there was a significant period of erosion and incision which removed the plug of sediment deposited in Terrace Group 3 and resulted in the deposition of a reworked terrace group further downstream, Terrace Group 4. This may reflect 2 things:

(1) A decrease in rainfall, localising erosion and deposition along the existing river course; or

(2) A change in base-level

A further possibility is that Terrace Group 4 was deposited contemporaneously with Terrace Group 3 from smaller amounts of sediment passing through the gorge and forming a lower level. However, it is more likely that Terrace Group 4 was deposited subsequently to Terrace Group 3 associated with a lowering in base-level.

The deposition of Terrace Group 4 was followed by a period of incision and the deposition of miscellaneous collections of terraces reflecting degradation of the channel. This is Stage E in the drainage history.

5.5 SUMMARY

Although the drainage history of the Rambla de Lucainena is currently limited in its implications concerning palaeoclimatic significance due to the problems of dating, this study has demonstrated the potential to provide information about semi-arid areas during the Quaternary. Specifically, this study has revealed potential evidence for periods of lower temperatures, in the form of fractured clasts, as well as evidence of pluvial periods involving rapid aggradation, partially pronounced by a gorge providing a natural damming point facilitating natural ponding and aggradation.

Deciphering the palaeoclimatic record from local tectonic signatures and obtaining greater dating controls would enhance this work. The dating of some of the more important terrace groups such as 3 and 4 may be attempted in the future through the use of optical luminescence.

6.0 CONCLUSIONS

This work was initiated to help complete the regional picture of drainage evolution in the Quaternary of SE Spain. Little of the work on the Neogene fill of the sedimentary basins of SE Spain has concentrated on the Quaternary, it has mainly dealt with the older deposits of the Messinian and Tortonian (i.e. Dronkert, 1976; Roep *et al.*, 1979; Van de Poel, 1991; Haughton, 1994). Some of the more recent work has concentrated on the Pleistocene dissectional history (Harvey, 1987; Harvey & Wells, 1987; Mather *et al.*, 1991) and the evolution of the drainage basins during the Plio/Quaternary (Mather, 1993b) to which this work will add.

Much of the Quaternary drainage history of SE Spain, like that of other semi-arid areas, has previously been interpreted principally in terms of neotectonic events (Harvey & Wells, 1987; Mather, 1993a; Mather, 1993b; Mather & Harvey, 1995). These interpretations are frequently complicated by the difference between temperate and semi-arid regions. This study has emphasised the difference between the fluvial processes occurring in semi-arid and temperate regions and illustrates the need to treat these areas differently, a fact which is tacitly assumed in most studies, but rarely considered when making detailed interpretations. For example, this project has illustrated the problems of tributary bedload build up close to the confluence with the main channel in semi-arid areas, due to incompetent flow in the main channel relative to its short tributaries. It has been demonstrated that this can lead to problems of raised terrace elevations at tributary intersections and variation in the sedimentological characteristics of terraces close to tributary junctions. The potential of these problems to complicate the correlation of fluvial terrace levels in semi-arid areas has also been established. This is one of the first pieces of work to bear these sorts of differences in mind (*cf.* Mather, 1993a). Often these problems are ignored and terrace correlation in semi-arid areas is carried out based on the same assumptions of those of temperate regions, a situation which may cause problems during correlation as illustrated in this thesis.

Unlike other studies on the Quaternary drainage history of SE Spain this study set out to filter out the effects of neotectonics on the drainage evolution of the Rambla de Lucainena and to decipher the more interesting palaeoclimatic significance of information recorded in the terrace groups of the Lucainena catchment. In doing this it has demonstrated the potential of studies such as this one to develop the understanding of the palaeoclimate of SE Spain during the Quaternary, which is currently poorly understood.

In the Rambla de Lucainena four significant terrace groups have been identified reflecting changes in base-level. Of these two have demonstrated palaeoclimatic significance, Terrace Groups 2 and 3.

Terrace Group 2 is a particularly interesting phase which illustrated the effects of rapid sedimentation and documented some intriguing sedimentological characteristics in the form of fractured clasts. These fractured clasts have been attributed to periglacial conditions, suggesting regular temperature oscillations close to 0°C during the Quaternary, which is previously undocumented in this part of SE Spain. However, periglacial features have recently been identified in the Cordoba Province of SE Spain (Torres-Giron & Recio-Espejo, 1997), roughly 200 km west of the study area. The evidence in the Cordoba province is found at greater heights than is witnessed in the Lucainena basin, but as there are few other documented sites of periglacial evidence in SE Spain this may be a site specific factor. No other sites of periglacial evidence have been documented closer to the study area than this. There are several explanations for this lack of evidence, firstly that the conditions for preservation of these features were only suitable in the facies of Terrace Group 2 of the Rambla de Lucainena and secondly that other periglacial features have been identified elsewhere in this region but due to the assumption of dry glacials during the Quaternary of SE Spain (Harvey, 1990) have been attributed to other mechanisms. To confirm the existence of periglacial conditions within the Quaternary of this region further evidence needs to be uncovered and workers need to consider the possibility of periglacial mechanisms when interpreting deposits. This previously undocumented evidence is definitely worthy of detailed future study to help refine the interpretation of the regional palaeoclimate during the Quaternary.

Terrace Group 3 recorded a significant palaeoclimatic episode yielding large volumes of aggradational fines. Periods of Quaternary alluvial aggradation during the Quaternary in the western Mediterranean have previously been attributed to dry glacial climatic phases (Rohdenburg & Sabelberg, 1973; Harvey, 1984) where aggradational phases are associated with less vegetational stabilisation (Mather, 1993a). However, the evidence within the facies of this terrace group suggests that aggradation here may be associated with pluvial periods providing an alternate mechanism of aggradation and suggesting periods of continuous rainfall during the Quaternary. This indicates that the palaeoclimate was at times much wetter during the Quaternary than previously interpreted and possibly more representative of a temperate environment.

The evidence recorded within both of these terrace groups indicates that the previous interpretations of palaeoclimate suggesting a dry semi-arid/arid climate during the Quaternary with increasing aridity during European glacials (Harvey, 1990; Mather, 1993a) are far too simplistic and that the climate of SE Spain during the Quaternary was infact much more variable and closer to a temperate climate at times. However, whether or not these pluvial periods correlate with these glacials is currently unknown. This demonstrates the need for further investigation into the palaeoclimatic significance of fluvial landforms in SE Spain, which should not simply be used as evidence of neotectonic activity.

The full regional palaeoenvironmental significance of the evidence within these two terrace groups cannot currently be established due to the lack of dating controls on these two episodes. This is an area which needs to be addressed as the focus of further work. As with all the Quaternary deposits of this area, dating is a problem and has only been achieved in a few instances (i.e. Harvey & Wells, 1987), however, possible dating tools which could be investigated for these terrace groups include optical luminescence, palynology, radiocarbon and isotopic dating. Once dates have been established it will be possible to fit the events recorded within the terrace groups of the Rambla de Lucainena into the regional picture. For example, Harvey & Wells (1987) have established four Quaternary terrace levels associated with the Feos/Aguas fluvial system A-D which feeds into the Rio Alias in the lowest reaches of the Rambla de Lucainena. Due to the close proximity of the

Feos/Aguas and Lucainena deposits it is possible that the youngest terrace level of the Feos/Aguas drainage system, D, which forms a thick aggradational layer, may be of similar age to the aggradational fines of Terrace Group 3 in the Lucainena drainage system. One carbon date has been established for the upper part of the stage D terrace level 2310 =80/-90 BP suggesting a Holocene age for these terrace gravels (Harvey & Wells, 1987). If a date could be obtained for Terrace Group 3 of the Lucainena drainage system then it may be possible to correlate these aggradational episodes. This has potential importance as the current explanation for the deposition of the Stage D deposits of the Aguas/Feos is attributed to differential uplift and local tectonics with the climate being suggested to be one of a dry glacial environment. If these deposits are of similar age and origin there is the potential to address this theory and determine more about the palaeoenvironment at this time.

Dating is also important for the deposits of Terrace Group 2 to enable correlation with other periglacial deposits such as those of the Cordoba Province which are currently dated at 80 000 years BP (Torres-Giron & Recio-Espejo, 1997). If the periglacial deposits of the Rambla de Lucainena are also of this age then it may suggest that periglacial conditions were prevalent across much of SE Spain during this part of the Quaternary and would emphasise the need to re-evaluate the palaeoclimatic models of this area during the Quaternary, highlighting the need for investigation to find further evidence of periglacial activity.

Dating controls on the Quaternary terrace groups would also help to tie in the drainage capture events of the Rambla de Lucainena with those occurring in the rest of the region. For example the capture of the Rambla Honda, the major tributary of the Rambla de Lucainena, has been suggested on the basis of morphological and sedimentological data, to have occurred at some point between the deposition of Terrace Group 1 and Terrace Group 2. Therefore, if dates could be established for these terrace groups then the age range at which this capture took place could be determined along with the relative age of the subsequent capture of the upstream Lucainena.

This project has also established the importance of understanding contemporary processes occurring within the modern day catchment and the value of using such evidence in interpreting past fluvial landforms. Furthermore, this process work has demonstrated that when considering erodability it is not sufficient just to look at the susceptibility of a rock to erosion but that the storage capacity of a catchment also needs to be considered. Analysis of both the erosion rates and storage capacity of the different parts of the catchment has enabled the interpretation of the significance of the relative abundance of different lithologies present in the Quaternary terrace gravels. This has made it possible to distinguish important episodes recorded within the Quaternary terrace groups, for example, in Terrace Group 1, lower schist levels than would have been anticipated from the higher erosion rates were found, which has been attributed to the fact that the Schist was not fully captured at this time. The facies variations of Terrace Group 2 also appear to be most readily explained by a combination of the erosion rates and storage capacity of different parts of the catchment. This evidence has illustrated the need for an understanding of the contemporary processes occurring within a catchment prior to the interpretation of the drainage history and indicates that all studies of this type should take this integrated approach.

In conclusion, the reconstruction of the first order drainage history can no doubt be refined to a more detailed chronology, although the purpose of such an exercise may be limited. However, it has so far allowed important features to be recognised which have significant implications on the drainage history and palaeoclimate. Previous work has concentrated on the reconstruction of the palaeodrainage with reference to neotectonics rather than the palaeoclimatic variability of the region (e.g. Harvey & Wells, 1987; Mather & Harvey, 1995). Further work needs to filter out the morphological effects of neotectonics so that more reliable palaeoclimatic interpretations may be obtained.

Other areas of interest which this thesis has demonstrated are worthy of further research, but were beyond the scope of the current work are:

(1) Geochemical analysis, which has been identified through this work as a potential correlation tool for terrace studies. However, this preliminary study has shown that

this tool needs to be used with some caution to allow for the possible effects of reworking of sediments or derivation of sediments from similar source areas. This technique needs to be investigated in more detail to determine its full potential. It may be that it could be used to refine the detail obtained by other terrace correlation techniques such as heavy mineral analysis.

(2) The discovery of microfossils within Terrace Group 3 has the potential to yield more information about the freshwater ostracod assemblage in SE Spain which is currently an under-researched area. This in turn could help to enhance the understanding of both the palaeoclimate and palaeoenvironment during the deposition of this terrace group, and would aid in the interpretation of the palaeoclimate during the Quaternary of this region.

REFERENCE LIST

Addicott, W.M., Snavely, P.D. Jr., Bukry, D. & Poore, R.Z. 1978. Neogene stratigraphy and palaeontology of southern Almeria Province, Spain: An overview. *U.S. Geological Survey Bulletin,* 1454, 49.

Amor, J.M. & Florschutz, F. 1964. Results of the preliminary palynological investigation of samples from a boring in Southern Spain. *Boletin de la Real Sociedad Espanola de Historia Natural,* 62, 251-255.

Ashmore, P. 1991. Channel morphology and bed load pulses in braided, gravel-bed streams. *Geografiska Annaler*, 73a, 37-51.

Baker, V.R. 1977. Bed load transport by natural rivers. *Water Resources Research,* 13, 303-312.

Ballance, P.F. & Gregory, M.F. 1991. Parnell Grits - Large subaqueous volcaniclastic gravity flows with multiple particle-support mechanisms. In: *Sedimentation in Volcanic Settings*, The Society of Economic Palaeontologists and Mineralologists, 45, 189-200.

Bell, M. & Walker, M.J.C. 1992. *Late Quaternary environmental change: physical and human perspectives.* Longman, Harlow.

Benito, G., Gutierrez, M. & Sancho, C. 1992. Erosion rates in badland areas of the central Ebro Basin (NE- Spain). *Catena*, 19, 269-286.

Benn, P.C. & Erskine, W.D. 1994. Complex channel response to flow regulation: Cudgegong River below Windamere Dam, Australia. *Applied Geography*, 14, 2, 153-168.

Best, J.L. 1986. The morphology of river channel confluences. *Progress in Physical Geography*, 10, 157-174.

Best, J.L. 1987. Flow dynamics at river channel confluences: Implications for sediment transport and bed morphology. In: *Recent developments in fluvial sedimentology*. The Society of Economic Palaeontologists and Mineralologists, 39, 27-35.

Best, J.L. 1988. Sediment transport and bed morphology at river channel confluences. *Sedimentology*, 35, 481-498.

Blikra, L.H. & Longva, O. 1995. Frost shattered debris facies of Younger Dryas age in the coastal sedimentary successions in western Norway; palaeoenvironmental implications. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 118, 1-2, 89-110.

Bridgland, D.R. 1986. *Clast lithological analysis*. Quaternary Research Association Technical Guide, 3, 1- 33.

Bridgland, D.R. 1988. The Pleistocene fluvial, stratigraphical and palaeogeography of Essex. *Proceedings of the Geological Association*, 99, 291-314.

Bridgland, D.R. 1994. *Quaternary of the Thames*. Geological Review Series 7. Chapman and Hall, London.

Briggs, D. 1981. *Sources and methods in geography- Sediments*. Butterworths, London.

Bristow, C.S., Best, J.L. & Roy, A.G. 1993. Morphology and facies models of channel confluences. *Special Publications of the International Association of Sedimentologists*, 17, 91-100.

Capel Molina, J.J. 1990. Riesgos climaticos; desertificacion y fluctuation climatica actual. *Boletin Geologico y Minero*, 101, 4, 108-116.

Campbell, I.A. 1970. Micro-relief measurements on unvegetated shale slope. *Professional Geographer,* 22, 215-220

Chatters, J.C. & Hoover, K.A. 1992. Response of the Columbia River Fluvial System to Holocene Climatic Change. *Quaternary Research*, 37, 42-59.

Chen, H., Lin, X., Guan, K. & Xu, J. 1994. Early Pleistocene deposits and their lower boundary (Q/N) in the Tien Shan, Xinjiang region. *Quaternary Sciences*, 1, 38-47.

Church, M. 1995. Geomorphic reponse to river flow regulation: Case studies and time scales. *Regulated rivers: research and management*, 11, 1, 3-22.

Cita, M.B. & Colombo, M.R. 1979. Late Neogene. *Deep sea drilling project; Initial report*. 47, 1, 391-417.

Collinson, J.D. & Lewin, J. 1983. Modern and ancient fluvial systems: an introduction. *Special Publications of the International Association of Sedimentologists*, 6, 1-2.

Cooke, R.U. 1979. Laboratory simulation of salt weathering processes in arid environments. *Earth Surface Processes,* 4, 347-359.

Cooke, R.U. & Smalley, I.J. 1968. Salt Weathering in Deserts. *Nature*, 220, 1226-1227.

Cooke, R., Warren, A. & Goudie, A. 1993. *Desert geomorphology*. UCL Press Ltd, London.

Davenport, C.A. & Ringrose, P.S. 1985. Fault activity and palaeoseismicity during Quaternary time in Scotland - preliminary studies. In: *Earthquake Engineering in Britain* (An institution of Civil Engineers Conference), 143-155. Thomas Telford, London.

Dronkert, H. 1976. Late Miocene evaporites in the Sorbas Basin and adjoining areas. *Memoirs de la Societe Geologique de France,* 16, 341-361.

Dumas, B., Gueremy, P., Llenaff, R., & Raffy, J. 1978. Geomorphologie et neotectonique des pays Mediterraneens. *Paris, Centre National de Recherche Scientifique*, Publication de la Recherche cooperative sur programme, 461, 123-170.

Evans, A.M. 1993. *Ore Geology and Industrial Minerals- An Introduction.* Blackwell Scientific Publications, Oxford.

Fisher, R.V. & Schmincke, H.U. 1984. *Pyroclastic Rocks.* Springer-Verlag, New York., 472.

Fookes, P.G. & Vaughman, P.R. 1986. *A handbook of engineering geomorphology.* Blackie, London.

Geiger, F. 1970. Die Ariditat in Sudostspanien. *Stuttgarter Geographische Studien,* 77, 173-185.

Gibbard, P.L. 1985. *The Pleistocene history of the middle Thames valley.* Cambridge University Press, Cambridge.

Gibbard, P.L. 1994. *The Pleistocene history of the lower Thames valley.* Cambridge University Press, Cambridge.

Gibbard, P.L. & Allen, L.G. 1994. Drainage evolution in south and east England during the Pleistocene. *Terra Nova,* 6, 5, 444-452.

Gilman, A. & Thornes, J.B. 1985. *Land-use and Prehistory in Spain.* Allen & Unwin, London.

Glicken, H. 1991. Sedimentary Architecture of large volcanic-debris avalanches. In: *Sedimentation in Volcanic Settings*, The Society of Economic Palaeontologists and Mineralologists, 45, 99-106.

Goudie, A. 1970. Experimental investigation of rock weathering by salts. *Area* Institute of British Geographers, 4, 42-48.

Green, C.P. & McGregor, D.F.M. 1980. Quaternary evoltution of the river Thames. In: *The shaping of southern England.* Jones, D.K.C. (ed.), Institute of British Geographers Special Pub. 11, Academic Press, London, 177-202.

Green, C.P. & McGregor, D.F.M. 1983. Lithology of the Thames gravels. In: *Diversion of Thames.* Rose, J. (ed.), Field Guide, Quaternary Research Association, Cambridge, 24-28.

Green, C.P. & McGregor, D.F.M. 1987. River terraces: A stratigraphic record of environmental change. In: *International Geomorphology.* Gardiner, V. (ed.), Wiley, Chichester, 1, 977-987.

Green, C.P., Hey, R.W. & McGregor, D.F.M. 1980 Volcanic pebbles in Pleistocene gravels of the Thames in Buckinghamshire and Herefordshire. *The Geological Magazine*, 117, 59-64.

Green, C.P. McGregor, D.F.M. & Evans, A. 1982 Development of the Thames drainage system in Early and Middle Pleistocene times. *The Geological Magazine*, 119, 281-290.

Gregory, K.J. 1976. Drainage networks and climate. In: *Geomorphology and Climate.* Derbyshire, E. (ed.), Wiley, London, 289-318.

Gurnell, A., Downward, S.R. & Jones, R. 1994. Channel planform change on the River Dee meanders. *Regulated rivers: Research and Management*, 9, 4, 187-204.

Haigh, M.J. 1977. The use of erosion pins in the study of slope evolution. *British Geomorphological Research Group Technical Bulletin.*, 18, 31-49.

Hallsworth, C.R., Morton, A.C. & Dore, G. 1996. Contrasting mineralogy of Upper Jurassic sandstones in the Outer Moray Firth, North Sea; implications for the evolution of sediment dispersal patterns. *Geological Society Special Publications*, 114, 131-144.

Harker, 1993. Fracture patterns in clasts of diamictites (? tillites). *Journal of the Geological Society*, 150, 251-254.

Harvey, A.M. 1984. Aggradation and dissection sequences on Spanish alluvial fans: influence on morphological development. *Catena*, 11, 289-304.

Harvey, A.M. 1987. Patterns of Quaternary aggradational and dissectional landform development in the Almeria region, southeast Spain: a dry-region, tectonically active landscape. *Die Erde*, 118, 193-215.

Harvey, A.M. 1990. Factors influencing Quaternary alluvial fan development in southeast Spain. In: *Alluvial fans: A field approach*. Rachocki, A.H. & Church, M. (eds.). John Wiley & Sons, 247-269.

Harvey, A.M. 1991. The influence of sediment supply on the channel morphology of upland streams: Howgill Fells, Northwest England. *Earth Surface Processes and Landforms*, 16, 675-684.

Harvey, A.M. & Wells, S.G. 1987. Response of Quaternary fluvial systems to differential epeirogenic uplift: Aguas & Feos river system, southeast Spain. *Geology*, 15, 689-693.

Haughton, P.D.W. 1994. Deposits of deflected and ponded turbidity ents, currents, Sorbas basin, southeast Spain. *Journal of Sedimentary Research*, A64, 2, 233-246.

Hey, R.D. 1986. River response to inter-basin water transfers: Craig Goch feasibility study (Wales, UK). *Journal of Hydrology*, 85, 3-4, 407-421.

Hey, R.D. & Thorne, C.R. 1984. Flow processes and river channel morphology. In: *Catchment experiments in fluvial geomorphology*. Proc. IGU Commision meeting, Exeter and Huddersfield 1981, Geo Books, Norwich, 489-514.

Hockney, B. 1970. An improved co-ordinate system for particle shape representation. *Journal of Sedimentary Petrology*, 40, 1054-1056.

Hsu, K.J., Montadert, L., Bernoulli, D., Cita, M.B., Garrison, R.E., Kidd, R.B., Melieres, F., Muller, C. & Wright, R. 1977. History of the Mediterranean salinity crisis. *Nature*, 267, 399-403.

Huckleberry, G. 1994a. Contrasting channel response to floods on the middle Gila River, Arizona. *Geology*, 22, 12, 1083-1086.

Huckleberry, G. 1994b. The 1983 and 1993 floods in southern Arizona; implications for high frequency climate change and channel dynamics. *Abstracts with Programs- Geological Society of America*, 26, 7, 236.

Jones, R.L. & Keen, D.H. 1993. *Pleistocene environments in the British Isles*. Chapman & Hall, London.

Keeble, A.B. 1971. Freeze-thaw cycles and rock weathering in Alberta. *Alberta Geographer*, 7, 34-42.

Kirkby, R.P. 1969. Morphometric Analysis of Glaciofluvial Terraces in the Esk Basin, Midlothian. *Institute of British Geographers Transactions*, 48, 1-18.

Krauskopf, K.B. 1979. *Introduction to Geochemistry*. McGraw-Hill Book Company, London.

Leopold, L.B., Wolman, M.G. & Miller, J.P. 1964. *Fluvial Processes in Geomorphology*. W.H. Freeman, San Fransisco.

Lowe, J.J & Walker, M.J.C. 1997. *Reconstucting Quaternary Environments*. Longman, London.

Martin, J.M. & Braga, J.C. 1994. Messinian events in the Sorbas Basin in southeastern Spain and their implications in the recent history of the Mediterranean. *Sedimentary Geology,* 90, 257-268.

Mather, A.E. 1993a. Basin inversion: Some consequences for drainage evolution and alluvial architecture. *Sedimentology*. 40, 1069-1089.

Mather, A.E. 1993b. Evolution of a Pliocene fan delta: links between the Sorbas and Carboneras Basins, SE Spain. *Special Publications of the International Association of Sedimentologists*, 20, 277-290.

Mather, A.E. & Harvey, A.M. 1995. Controls on drainage evolution in the Sorbas Basin, SE Spain. *Mediteranean Quaternary River Environments*. Macklin, M. Lewin, J. and Woodward, J. (eds.), Balkema, 65-76.

Mather, A.E. & Westhead, R.K. 1993. Plio/Quaternary Strain of the Sorbas Basin, S.E. Spain: Evidence from Sediment Deformation Structures. *Quaternary Proceedings*, 3, 17-24.

Mather, A.E. Worcester, A.M. Harvey, A.M. & Brenchley, P.J. 1991. Halokinetic deformation of Quaternary river terraces in the Sorbas basin, South East Spain. *Zeitschrift fur Geomorphology, N.F.*, 82, 87-97.

McGreevy, J.P. 1981. Some perspectives on frost shattering. *Progress in Physical Geography*. 5, 56-75.

McGregor, D.F.M. & Green, C.P. 1986. Early and middle Pleistocene gravel deposits of the Thames - Development of a lithostratigraphic model. In: *Clast Lithological Analysis*. Bridgland, D.R. (ed.), Technical guide no.3, Quaternary Research Association, Cambridge, 95-115.

McIntosh, P.D., Eden, D.N. & Burgham, S.J. 1990. Quaternary deposits and landscape evolution in northeast Southland, New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 81, 95-113.

Morton, A.C. 1991 Geochemical studies of detrital heavy minerals and their application to provenance research. In: *Developments in Sedimentary Provenance Studies*. Geological Society Special Publication no. 57, 31-45.

Mosley, M.P. 1975. A device for the accurate survey of small scale slopes. *British Geomorphological Research Group Technical Bulletin.,* 17, 3-6.

Nolan, K.M. & Marron, D.C. 1985. Contrast in stream-channel response to major storms in two mountainous areas of California. *Geology,* 13, 2, 135-138.

Palmer, B.A., Alloway, B.V. & Neall, V.E. 1991. Volcanic-debris-avalanche deposits in New Zealand- Lithofacies organisation in unconfined, wet-avalanche flows. In: *Sedimentation in Volcanic Settings*, The Society of Economic Palaeontologists and Mineralologists, 45, 89-98.

Park, C.C. 1981. Man, river systems and environmental impacts. *Progress in Physical Geography,* 5, 1-31.

Peterson, G.L. 1980. Broken rocks in the Desert Environment. In: *Geology and mineral wealth of the California desert*. Fife, D.L. and Brown, A.R. (eds.), South Coast Geological Society, 403-408.

Petts, G.E. 1979. Complex response of river channel morphology subsequent to reservoir construction. *Progress in Physical Geography,* 3, 3, 329-362.

Petts, G.E. 1987. The regulation of the Derbyshire Derwent. *East Midland Geographer*. 10, 2, 54-63.

Petts, G.E. & Foster, I.D.L. 1990. *Rivers and Landscape*. Edward Arnold, London.

Petts, G.E. & Thomas, M.C. 1986. Channel aggradation below Chew Valley Lake, Somerset, U.K. *Catena*, 13, 3, 305-320.

Pickering, K.T. 1983. Small scale synsedimentary faults in the Upper Jurassic 'Boulder Beds'. *Scottish Journal of Geology*, 19, 169-81.

Pickering, K.T. 1984. The Upper Jurassic 'Boulder Beds' and related deposits: a fault- controlled submarine slope, NE Scotland. *Journal of the Geological Society*, 141, 357-374.

Postma, G. 1984. Mass flow conglomerates in a submarine canyon: Abrioja fan delta, Pliocene, Southeast Spain. In: *Sedimentology of Gravels and Conglomerates*. Koster, E.H. and Steel, R.J. (eds.), Canadian Society of Petroleum Geology Memoir, 10, 237-258.

Richards, K. 1982. *Rivers- Form and Process in Alluvial Channels*. Methuen, London.

Rios, J.M. 1978. The Mediterranean coast of Spain and the Alboran Sea, In: *The ocean basins and their margins*. Nairn, A.E.M., Kanes, W.H. & Stehli, F.G. (eds.), The Western Mediterranean: New York, Plenum, 4b, 1-66.

Robinson, D.A. & Williams, R.B.G. 1969. Salt weathering of rock specimens of varying shape. *Area*, 14, 4, 293-299.

Roep, Th.B., Beets, D.J., Dronkert, H. & Pagnier, H. 1979. A prograding coastal sequence of wave building structures of Messinian age, Sorbas, Almeria, Spain. *Sedimentary Geology*, 22, 135-163.

Rohdenburg, H. & Sabelberg, U. 1973. Quatare Kleinzyklen in Westlichen Mediterrangebiet und ihre Auswirkungen auf die Reilief- und Bodenentwicklung. *Catena*, 1, 71-80.

Roy, A.G. & Roy, R. 1988. Changes in channel size at river confluences with coarse bed material. *Earth Surface Processes and Landforms,* 13, 1, 77-84.

Rumsby, B.T. & Macklin, M.G. 1994. Channel and floodplain response to recent abrupt climate change; the Tyne Basin, northern England. *Earth Surface Processes and Landforms*, 19, 6, 499-515.

Sala, M. 1988. Slope runoff and sediment production in two Mediterranean mountain environments. In: *Geomorphic processes in environments with strong seasonal contrasts*. Vol.1: Hillslope Processes. Imerson, A.C. & Sala, M. (eds.). Catena Suppl., 12, 13-29.

Schumm, S.A. 1972. *River Morphology*. Dowden, Hutchinson & Ross, Inc. Pennsylvania.

Schumm, S.A. 1977. *The Fluvial System*, Wiley & Sons, New York.

Schumm, S.A. 1981. Evolution and response of the fluvial system, sedimentological implications. In: *Recent and ancient non-marine depositional environments: models for exploration*. The Society of Economic Palaeontologists and Mineralologists, 31, 19-29.

Sherrard, J.J. & Erskine, W.D. 1991. Complex response of a sand-bed stream to upstream impoundment. *Regulated Rivers, Research and Management*, 6, 1, 53-70.

Smith, A.G. & Woodcock, N.H. 1982. Tectonic synthesis of the Alpine-Mediterranean region: A review. In: *Alpine-Mediterranean geodynamics*. Berckhemer, H. and Hsu, K. (eds.). American Geophysical Union Geodynamics Series, 7, 15-38.

Smith, B.J. & McGreevy, J.P. 1983. A simulation study of salt weathering in hot deserts. *Geografiska Annaler*, 65A, 1-2, 127-134.

Smith, G.A. 1986. Coarse-grained non-marine volcaniclastic sediment: Terminology and depositional processes. *Geological Society of America Bulletin*, 97, 1-10.

Smith, G.A. & Lowe, D.R. 1991. Lahars: Volcanic-Hydrologic events and deposition in the debris flow- Hyperconcentrated flow continuum. In: *Sedimentation in Volcanic Settings*. The Society of Economic Palaeontologists and Mineralologists, 45, 59-70.

Sneed. E.D. & Folk. R.L. 1958. Pebbles in the lower Colorado River, Texas, a study in particle morphogenesis. *Journal of Geology*, 66, 114-150.

Sperling, C.H.B. & Cooke, R.U. 1985. Laboratory simulation of rock weathering by salt crystallization and hydration processes in hot, arid environments. *Earth Surface Processes and Landforms*, 10, 541-555.

Tucker, M.E. & Wright, V.P. 1992. *Carbonate Sedimentology*. Blackwell Scientific Publications, Oxford.

Tanner, L.H. & Hubert, J.F. 1991. Basalt breccias and conglomerates in the Lower Jurassic McCoy Brook Formation , Fundy Basin, Nova Scotia: Differentiation of talus and debris flow deposits. *Journal of Sedimentary Petrology*, 61, 1, 15-27.

Thompson, S.M. & Campbell, P.L. 1979. Hydraulics of a large channel paved with boulders. *Journal of Hydraulic Research*, 17, 4, 341-354.

Thorne, C.R. & Lewin, J. 1982. Bank processes, bed material movement and planform development in a meandering river. In: *Adjustments to the fluvial system*. Rhodes, D.D. & Williams, G.P. (ed.), Proc. 10th geomorphology symposium, Binghampton, 1979. Allen & Unwin, 117-137.

Torres-Giron, M.L. & Recio-Espejo, J.M. 1997. Periglacial features of the Subbetic Mountains of southern Spain (Cordoba Province). *Journal of Quaternary Science*, 12, 4, 275-282.

Ui, T., Kawachi, S. & Neall, V. E. 1986. Fragmentation of Debris avalanche material during flowage- Evidence from the Pungarehu Formation, Mount Egmont, New Zealand. *Journal of Volcanology and Geothermal Research*, 27, 255-264.

Vita Finzi, C. 1969. *The Mediterranean valleys, geological changes in historic times*. Cambridge University Press.

Van de Poel, H.M. 1991. Messinian stratigraphy of the Nihjar Basin (S.E. Spain) and the origin of its gypsum-ghost limestones. *Geologie en Mijnbouw*, 70, 215-234.

Wells, A.W. & Bennett, M.R. 1996. A simple portable device for the measurement of ground loss and surface changes. *Zeitschrift fur Geomorphologie. N.F.*, 106, 255-265.

Wiejermars, R. Roep, Th. B. Van den Eeckhout, B. Postma, G. & Kleverlaan, K. 1985. Uplift history of a Betic fold nappe inferred from Neogene-Quaternary sedimentation and tectonics (in the Sierra Alhamilla and Almeria, Sorbas and Tabernas basins of the Beitic Cordilleras, SE Spain). *Geologie en Mijnbouw*, 64, 397-411.

Wielchowsky, C.C. & Stow, S.H. 1975. Heavy mineral provenances of the Coker Formation and alluvial terrace deposits in Tuscaloosa County, Alabama. *Abstracts with programs - Geological Society of America*, 7, 4, 549.

Maps

1: 25 000 Mapa Topografico Nacional de Espana. Polopos 1031-III.

1: 50 000 Mapa Topografico Nacional de Espana. Sorbas 1031

1: 50 000 Mapa Topografico Nacional de Espana. Machael 1013

1: 50 000 Mapa Topografico Nacional de Espana. Tabernas 1030

1: 50 000 Mapa Topografico Nacional de Espana. Carboneras 1046