6. Discussion and Conclusions

6.1 Introduction

This study has considered the present day geomorphic form of the Pyrenean chain and its erosional history. This final chapter considers the implications of the results of these studies in the context of the modern orogen, previous work and theories described for the Pyrenees and the implications of the erosional history on the geomorphology and vice versa.

6.2 Thermochronology

The principal observation derived from the thermochronometric data is the asymmetric distribution of exhumation and erosion across the orogen. In the northern Pyrenees, a rapid pulse of exhumation at around ~30 Ma is recorded, that brought the rocks to within 1 km or less of the surface. Therefore, during the last 30 Ma only ~1 km or less of exhumation can have taken place, which if constant over time, gives a maximum rate of 0.033 kmMyr⁻¹. In comparison, samples situated to the south of the principal drainage divide show a different exhumational history. Samples close to the centre of the orogen in the south show a similar pulse of exhumation at 30 Ma to the northern samples. However, during this period of rapid exhumation, relatively less exhumation took place than in the north, with the modern day surface samples getting to a distance of ~2.5 km below the surface at ~30 Ma. Therefore in the last 30 Ma these rocks have been exhumed from depths of ~2.5 km below the surface, ~1.5 km greater than in the north. A further asymmetry is documented by samples on the southern margins of the Axial Zone, with rapid exhumation documented at around 20 Ma, then gradually slowing until the present day.

6.2.1 Implications for previous studies

Previous thermochronological studies in the Pyrenees also documented asymmetry in the exhumation history (Yelland, 1990; Morris et al., 1998; Fitzgerald et al., 1999). This broad observation is confirmed by the thermochronological data from this study and that of Gibson (2005). This data allows for a better understanding of the late stage history, by use of a lower temperature thermochronometer. This new data however, is not in complete
agreement with that published and described previously. Work by Fitzgerald et al. (1999),
identified a break or kink in the age-elevation relationship (AER) for their profile (Besiberri)
in the southern Pyrenees (figure 5.2). As was described in section 5.2.1, their vertical profile
was sampled over long horizontal distances and as such may be erroneous to interpret it as
one self-contained profile. If their data is split, so that the actual elevations and relief
permitted in the sampling region are shown, then it follows the interpretations proposed and
modelled in chapter 5, displaying little evidence for a kink in the AER (section 5.4.2.2.2). This
kink had previously been interpreted as evidence for a pulse of late Miocene
exhumation, with the samples remaining effectively constant with respect to the surface for a
period of at least 20 Myrs. This was used to support the hypotheses of Coney et al. (1996)
with regard to the southern flank of the Axial Zone being draped by syntectonic
conglomerates, effectively burying the mountain front and preventing further exhumation.

The observation, that this kink in the AER for the southern Pyrenees is not present, has
strong implications for attempting to invoke a period of stasis in the Axial Zone of the
Pyrenees. This lack of evidence in the new data, suggests that the Axial Zone of the
Pyrenees was never draped with sediments to a sufficient extent to shut off exhumation.

Further evidence of this comes from the thermochronological data on the southern margin of
the Axial Zone at Barruera. These samples record a rapid exhumation at 20 Ma and then
gradually slowing, with relatively rapid exhumation until around 10 Ma. These observations
do not fit with the concept that the entire southern flank of the orogen, was shut down during
this period. They suggest rather that the large conglomeratic deposits found today to the
south of the Axial Zone, probably did not drape the southern flank to a sufficient degree to
slow or inhibit the exhumation of the southern Pyrenees.

6.2.2 Transition from syn- to post-orogenic

It is clear from the thermochronological data, describing such large quantities of exhumation
and erosion over such short time intervals that the events recorded by the apatite fission track
data are not post-tectonic in origin. The transition from a syn-tectonic to a post-tectonic
orogen may be simply defined as when the two tectonic plates or units stop moving with
respect to one another. However, it is not as easy in practise to simply mark a point in time,
when the orogen suddenly switched off and became post-orogenic. The
thermochronological data from the Pyrenees points to a more gradual shut down, with parts
of the mountain belt entering the post-orogenic phase earlier than others.
The northern Pyrenees record the first shutting down of active tectonics. The lack of large amounts of exhumation (~1 km or less) beyond 30 Ma suggests that this part of the mountain belt shut down at an early stage. This is supported by observations of the sedimentation record in the Aquitaine Basin (Morris, 1999). The Miocene units within the Aquitaine Basin record an equivalent exhumation rate in the orogen of 0.02 kmMyr\(^{-1}\). This is in good agreement with the modelled exhumation rate in this study for the northern Pyrenees of 0.033 kmMyr\(^{-1}\). The slightly higher amount derived from modelling in this study could be due to resolution and timings of exhumation permitted. No knowledge of the samples after they have passed the top of the PRZ is available and therefore the 1 km of exhumation is an upper limit and less exhumation may have taken place with a corresponding drop in exhumation rate. Previous studies (Teixell, 1998; Morris, 1999) appeal to a possible sediment bypass of the Aquitaine basin during this time to explain the low denudation and sedimentation rates. These thermochronology results suggest that such a bypass is not required and that such low rates of sedimentation are possible to achieve.

The available data in the southern Pyrenees allows a more complex story to be unravelled. The Maladeta profile, shows that post 30 Ma ~2.5 km of exhumation has taken place. With these limited constraints it is not possible to place an exact time on when this profile entered a post-orogenic setting, but the discrepancy in ages and rates compared to those across the drainage divide suggest that it became post-orogenic at some point after 30 Ma, later than in the north. The rapid exhumation evidenced in the Barruera profile, suggest that this region was still undergoing active deformation until after 20 Ma. The considerably greater amounts and rates of exhumation here at this time compared to Maladeta indicate that some major structure must have been active late in the history of the orogen, to give this discrepancy in rates and amounts of exhumation (0.22 kmMyr\(^{-1}\) at Barruera compared to 0.086 kmMyr\(^{-1}\) at Maladeta between 19-9 Ma). The Senet thrust has been documented to have been active late in the orogen’s history (Gibson, 2005), and so could have provided a mechanism by which this could have taken place. Again it is difficult to pin down an exact point in time when this part of the orogen became post-orogenic. The rapid rates required to achieve the observed ages in both the AFT and AHe systems, suggest that this shut down may be as late as 10 Ma, considerably later than previously considered for this southern margin of the Axial Zone (Sinclair et al., in press). To the south of the Axial Zone work on the foreland thrust belt suggest that it was last active at around 24.7 Ma (Meigs et al., 1996).

It can therefore be seen that the transition from a syn- to a post-orogenic setting is not a single event, but in fact a gradual process (figure 6.1). These observations show that, whilst
the northern Pyrenees were in a post-orogenic setting, the southern Pyrenees were still active, possibly for up to 15-20 Myrs longer in isolated areas. So in the Pyrenees the switch from syn- to post-orogenic was diachronous across the orogen, with first the north shutting down, then followed by either the regions close to the drainage divide in the south or the foreland fold and thrust belt, followed by the regions on the southern margins of the Axial Zone.

6.3 Macrogeomorphology and Thermochronology

This section integrates the observed geomorphology with the data derived from the thermochronology to place possible timings on the controls on the post-orogenic setting.

6.3.1 Summary of geomorphic results

An asymmetry exists within the observed macrogeomorphology of the Pyrenees, both in its overall form and at a catchment scale. Morphometric parameters extracted for a number of both northerly and southerly draining catchments show that the northern catchments have steeper slopes and lower minimum elevations than their southerly draining counterparts. These observations fit the expected tectonic signal if an asymmetric mountain belt simply downwears in a post-orogenic setting.

An enhanced northerly glaciation has carved the valleys of the northern catchments to lower elevations than in the south, with glaciers often reaching out into the foreland in the north in past glaciations.

The lithological distribution of crystalline massifs control the position of the principal drainage divide in the orogen due to their greater resistance to erosion than the surrounding lithologies.
6.3.2 Timings on the controls of orogenesis

6.3.2.1 Climate

Recent work has suggested an increase erosion rates in the last 2–4 Myr in both active and inactive orogens around the globe attributed to a change in global climate linked to the onset of northern hemisphere glaciations (Zhang et al., 2001; Zachos et al., 2001). These observations are based on a general global increase in sedimentation rate around this time. In the Pyrenees however, no such increase in exhumation rate is evidenced by the thermochronological data, with no very young ages being found. This does not suggest that no such climate change or enhanced erosional regime occurred, simply that if it did take place in the Pyrenees, it was of insufficient magnitude to be recorded in the thermochronological data. A short calculation may be performed in order to show how much erosion and exhumation is required during the last 4 Ma for a climatic signal to be preserved in the thermochronometric record. For a simple case assuming an age fixed at a closure temperature of ~70°C, a geothermal gradient of 30°Ckm⁻¹ and an average surface temperature of 10°C, ~2km of exhumation would be required for a valley sample to record an AHe age. Therefore over the past 4 Ma, a rate of at least 0.5 kmMyr⁻¹ would be required in order to see a young AHe age in the valley samples. For an equivalent AFT age at least a further kilometre of exhumation would be required. As the thermochronological data presented in this thesis shows, in the northern Pyrenees, where a climatic signal would be expected, only ~1 km or less exhumation has taken place since 30 Ma at a modelled average rate of 0.034 kmMyr⁻¹, considerably lower than that required to detect a signal at 4 Ma. On the basis of the thermochronology, the thermal modelling and these calculations it may be seen that there is no signal of post 4 Ma climate change recorded in the Pyrenees of sufficient magnitude to be detected by thermochronometers. It should be noted that such a signal has been proposed for the European Alps (Cederbom et al., 2004) based on thermochronological data from the Alpine foreland and so it is interesting that no such signal is detected in the neighbouring Pyrenees.

6.3.2.2 Lithology

The distribution of Hercynian Crystalline Massifs (HCMs) within the Axial Zone of the Pyrenees controls the present day location of the principal drainage divide. Sedimentary evidence (section 3.4.3), has evidenced granitic material as far back as 54.5 Ma (Gaemers, 1978; Vincent, 2001), with a gradual increase in granitic source material through time, with
the syn-tectonic conglomerates to the south of the orogen preserving clasts from the HCMs throughout their history (Mellere, 1993; Vincent, 1993; 2001). Preservation in northern deposits is poor, with some isolated clasts found within the syn-tectonic Poudinages de Palassou (Vergés et al., 1995). This record of continued erosion of HCMs over the last ~50 Ma suggests that they have been influencing the geomorphic form of the Pyrenees for a long period of time.

The thermochronological data in this study comes from these HCMs. The northern data allows only ~1 km of exhumation after 30 Ma. This and the presence of clasts of HCMs in the syn-tectonic conglomerates in the south at this time (Mellere, 1993; Vincent, 2001) suggest that the position of present day principal drainage divide has remained constant over the last 30 Ma. This makes the assumption that the massifs exposed today along the drainage divide were the same massifs that were exposed at 30 Ma and that they are simply dome like features and not having some complex shape such as a laccolith. The small amount of erosion and exhumation permitted by the thermochronological data suggests that this is probably the case and that the position of the modern drainage divide has been controlled by the HCMs for the last 30 Ma. The presence of massifs of which no trace in the Axial Zone remains today may have caused small fluctuations in the position of the divide, but its form would have generally remained constant.

The small amount of permitted exhumation after 30 Ma in the north (~1 km), also suggests that the modern drainage network has been relatively constant in position over this period. The modern system has relief of up to 1500m in parts and so if relief was present at around 30 Ma as the thermochronology modelling and mountain belt modelling (Beaumont et al., 2000b) suggest then the drainage network cannot have changed much over the last 30 Ma. It is not possible to determine if the southern network has remained constant based on the thermochronology, as the amount of exhumation post 30 Ma (~2.5 km) is significantly larger than the present day valley relief (up to 1.5 km). However, the interpretation of features such as the Sis conglomerate as Palaeovalleys (Vincent and Elliot, 1997), which now form large ridge and plateau features, suggest that the drainage network it is not as long-lived as that in the north.

6.3.2.3 Tectonics

The thermochronological data shows the gradual shut down of tectonics in the Pyrenees, until the entire mountain belt is in a post-orogenic setting. These observations suggest the
influence of tectonic forces on the Pyrenean geomorphic form, possibly as late as 10 Ma in certain southern regions. However the majority of the orogen has been in a post-orogenic setting for at least the last 20 Ma. The dominance of the tectonic signal in the macrogeomorphology shows that the inherited tectonic features from active orogenesis are the principal control on the post-orogenic form of the Pyrenees.

The low exhumation rates documented in the post-orogenic system of the Pyrenees contrast sharply with those observed in active orogens. Rates derived from thermochronology in actively uplifting orogens have been shown to be as high as 2-5 kmMyr\(^{-1}\) in the Himalaya (Zeitler et al., 1982; Burbank et al., 2003) and between 1 and 2.8 kmMyr\(^{-1}\) in the Southern Alps of New Zealand over sustained periods of time (3-8 Myrs) (Tippett & Kamp, 1993). In contrast rates derived for the Pyrenees in this study are orders of magnitude lower at 0.034 kmMyr\(^{-1}\) and 0.086 kmMyr\(^{-1}\) for the north and south respectively over the last 30 Ma.

6.3.3 Implications for other geomorphic studies

A recent study on the geomorphology of the Pyrenees (Babault et al., submitted), documented evidence and devised an explanation for the presence of high elevation peneplains within the orogen. These features have been documented by many of the early studies on the Pyrenean geology and geomorphology (e.g. Penck, 1894; de Sitter, 1952). The formation for these features is poorly understood and as such many varying interpretations have been suggested based on rapid uniform uplift and lowering of base level (e.g. de Sitter, 1952). The most recent work (Babault et al. submitted) appeals to the hypothesis of Coney et al. (1996) related to sediment ponding. This ponding and a subsequent drop in base level is argued to preserve these high elevation, low relief surfaces. The thermochronology is contradictory to this hypothesis and does not support such ponding of sediment in the Axial Zone (section 6.2.1). This thesis does not attempt to give an alternative explanation for the formation of these peneplains, but to show that they cannot be related to Axial Zone ponding of sediments.

Recent studies (Gaspar-Escribano et al., 2001; García-Castellanos et al., 2003) have focussed on the transition of the Ebro Basin from an internally drained to an externally drained system. The timing of this event is given at around late Miocene times, though its exact timing is unknown. It may be expected that such a considerable drop in base level would trigger enhanced erosion throughout the drainage basin, as the river cuts back up the basin.
The thermochronological data for the Pyrenees does not document this event. This is probably due to the size of the drainage basin and the small amount of erosion by isostatic rebound it would generate in the upper reaches of the catchments.

### 6.4 Conclusions

- An asymmetry exists in the Pyrenees, both in its overall topographic form and at a catchment scale. Morphometric parameters extracted for a number of northerly and southerly draining catchments show that northern catchments have steeper slopes and lower minimum elevations than their southern counterparts. This fits the expected tectonic signal if an asymmetric mountain belt simply downwears in a post-orogenic setting.

- The lithological distribution of the Axial Zone plays an important role in shaping the macrogeomorphology with the distribution of crystalline massifs controlling the location of the principal drainage divide. This is due to the resistance of the crystalline massifs to erosion compared to the surrounding lithologies defining the high elevations.

- An enhanced northerly glaciation aided by orographic precipitation and aspect, glaciated northerly catchments to lower elevations than their southerly counterparts and reached out into the foreland in the north during larger glaciations.

- Thermochronology results document a strong asymmetry to the exhumation and erosional history of the Pyrenees. Northerly draining vertical profiles display rapid exhumation at around 30 Ma and show ~1 km or less of exhumation after this time. In contrast, samples in the central Axial Zone to the south of the principal drainage divide show rapid exhumation at around 30 Ma but considerably more exhumation after this time (~2.5 km) than the northern profiles. Samples at the southern margins of the Axial Zone show rapid exhumation at around 20 Ma, with gradually decreasing exhumation after this time.
• A gradual, diachronous transition from an active to a post-orogenic condition is documented, with some isolated parts of the orogen remaining active after 20 Ma and possibly up until 10 Ma.

• The thermochronology evidence suggests that the Axial Zone of the Pyrenees, either north or south, was not draped by syn-orogenic conglomerates and that no pulse of exhumation in the Miocene is required to explain the observed age-elevation relationships.

• No evidence is recorded in the thermochronological data in the Pyrenees for an increase in exhumation rate corresponding to a change in climate in the last 4 Ma.

• The small amounts of erosion and exhumation documented in the north fit the sedimentary record in the Aquitaine basin and suggest that the form of the modern drainage divide has been controlled by the Hercynian Crystalline Massifs for at least the last 30 Ma.

• Modelling work has highlighted the importance of topography in the patterns displayed in age-elevation relationships and has shown that it should always be considered when analysing data or planning sampling strategies.
Figure 6.1 - Cartoon cross-section through the Pyrenees illustrating the timings for the transition from a syn- to a post-orogenic system. Information in brackets is source of age data: BAR - Barruera; MAL - Maladeta; MM - Mari Maña; ART - Arties.