Abstract

This report deals with the geological setting, the geological structures and lithology in the area around Camarasa, Spain located in the foreland of the Pyrenees. From the investigation done on these aspects a geological history is constructed of the area.

The means by achieving this goal is done by effectively recording the orientations of bedding, by describing the lithology in a detailed manner including the paleo-environment of deposition, and making accurate observations. The observations were made in different ways. One way was to make detailed sketches of the geological structures found around Camarasa; this is also called ‘Swiss geology.’ Another way was to directly draw the lithology observed onto the field map. The geological tools (e.g. hammer and compass) as well as having a proper field book and map proved to be indispensable. From all the data observed in the field a detailed geological map was constructed displaying the lithology and the structures seen in the area. Moreover, a complete stratigraphical column was created as well as several profiles.

The data shows that the Camarasa area is greatly dominated by folding and thrusting of lithological units. The lithology in the area varies from Triassic gypsum, to Cretaceous limestones, to early Eocene limestones, and to early to late Oligocene terrestrial deposits including lacustrine gypsum. The most readily apparent structures in the area are thrusts. There is a major hinterland dipping thrust in the north that contains cretaceous rocks and in the southeast another one but smaller containing Eocene / Oligocene rocks. These thrusts must have become active *after* the deposition of the last Oligocene rocks. The central hill, called Sant Salvador, proved to be a geological complexity that formed during the early Eocene as a foreland dipping antiformal stack. Subsequent periods of continued compression, thrusting, and erosion caused Sant Salvador to become heavily deformed. The reason why this area could become this heavily deformed is that the presence of gypsum throughout the area acts as a lubricant enabling the more resistant lithological units to become easily folded.

Introduction

This study deals with a part of the large Pyrenean orogene in northern Spain. The Pyrenean orogene formed during different stages of deformation. The Pyrenean orogene as they are now, is the result of the Alpine orogene, occurring between 60 and 20 million years ago (Beaumont et al.). The contampory Pyrenean orogen can be subdivided in different parts. A good study to the composition of the Pyrenean orogen was done by Choukroune, P and the ECORS team, who made the ECORS profile: a seismic profile through the Pyrenean orogen from north to south.

The part of the Pyrenean Orgogen that was covered in this study is the Serres marginals, characterized by thrusts dipping to different directions and some thrusts that are overlain by each other, i.e an antiformal stack structure (Choukroune et al., 1989). The Serres marginals belongs to the foreland of the Pyrenean orogen. One of the main characteristics of a foreland is the structure of the crust. Many faults and folds occur in the foreland

The aim of our study was to study in further detail these geological phenomena, occurring in the foreland by reconstructing the geological history of a specified area. This was done in an area near the village Camarasa in northern Spain, situated in the Serres Marginals. The fieldwork area was about 4km by 2.8 km big. It can be seen on one of the maps of our area, given in Appendix III. The geology of the area is dominated by sedimentary rocks, like carbonate rocks and conglomerates. Further, gypsum is also widespread in the area. The ages of the rock vary from Trias till Eocene. Finally, the region contains, as can be derived from the ECORS profile, some important thrust faults that were a major item in this study.

The main geomorphologic feature of the area is the Sant Salvador mountain, positioned in the middle of the map. This mountain still puzzles many geologists. In the north, the area is bounded by large cliffs, cut through by the river Segre. In the southwestern part of the region, three parallel orientated layers occur, that are called the 'Three Sisters'. Especially the western part of the region is characterized by forests, making it more difficult to do geological fieldwork. Around the river Segre, mainly at Camarasa, many agricultural terrains occur, that were not covered in this study.

In order to study the geological phenomena that are dominant in this region, different kind of observations were done. First of all the lithology was studied throughout the area. By correlating the lithologies of the area, a sedimentary column was constructed for the whole area. With this sedimentary column, units were defined and so a map could be constructed, based on this unit division. Further, strike and dip measurement were done of the layers and were also placed on the map. On the basis of these measurements, a structural interpretation could be made, in combination with other observations in the field (sketches etc). With this structural interpretation, different profiles were made through the area, in order to illustrate the structure of the upper crust of the area.

It is very important for the sedimentary column as well as for the profile to study the contacts between the layers very carefully in the field. It provides you much information about the geological history of the region. The region itself is dominated by many different types of contacts. Three main types of contacts were found. These are described below.

- (Angular) unconformity: one layer is bounded to another layer by an erosional surface. If the layers do not show a change in orientation (strike/dip), the contact is called an unconformity. If there is a change in orientation, the contact is called an angular unconformity. An (angular) unconformity is the result of uplift of a layer and subsequently erosion of this layer, forming an erosional surface. The second layer is deposited on this erosional surface, either in the same orientation of the layer below either in another orientation. A characteristic of an (angular) unconformity is: some small grains of the layer below are included in the layer that is deposited on this layer.
- Fault contact. When a thrust fault cuts through a packet of layers, an older layer is positioned on younger layers. Characteristics of thrust faults are the presence of fault gouge, (on a larger scale) footwall anticlines and hanging wall synclines and a very fast change in orientation of the layers. This last point is a good indicator for thrust faults, in order to distinguish them from folds. Folds have a more gradual change in orientation than thrust faults.
- Normal contact. If no evidence can be found for the first two types of contact, a normal contact can be present. This means that the successive layers were deposited over each other with no period of erosion.

When studying a contact in the field, evidence must be found in order to choose one of these possibilities for the contact.

Finally, by combining the lithological information with the profiles, a geological history could be made, describing the main geological phenomena that were dominant in a foreland of the Pyrenean orogene, which was the aim of our study. It became clear from our study that different phases of deformation were responsible for the complex structure of the Sant Salvador. Further, the material properties of gypsum had been very important for the occurrence of thrust faults.

Basic field mapping techniques

Standard geological equipment:

- Geological compass useful for measuring strike and dip of bedding
- A field/fact/blank topographical map of the area around Camarasa at a resolution of 1:10000
- A geological hammer
- A small bottle containing HCl to check on calcite in rocks
- A sand ruler useful for determining the grain size
- A loupe with magnification of 10x

Preparation

Before we entered the field area, we studied the area from air photos. From this, we traced some main lithological outcrops and identified dominant structures such as faults.

How to define lithological units

The lithology in the area of Camarasa varies greatly. In order to avoid using one colour for each type of rock that we encountered, we described the rock in terms of its origin, i.e. what were the environmental conditions that favoured this type of sediment to be deposited. This can be done by for example looking at any cross-bedding there might be, or more importantly looking at its fossil content. In addition, certain fossils are markers that not only describe the environmental conditions at the time, but also of the period in which these organisms lived giving an indication of the age of the rock. Once the environment has been established for an outcrop in a certain area, we correlated it with other such types of outcrops elsewhere in the area. The outcrop of a sequence of rocks can then be described as a lithological unit.

As already mentioned, the fieldwork area is positioned in foreland of the Pyrenees, characterised by many thrusts. In order to make a geological map, it is very important to distinguish the rocks by age. By doing this, the rocks that had been deposited locally can be distinguished from rocks that had been transported to this place.

We determined the age by two methods:

- Fossils
- The different contacts between the layers. For example, if a thrust occurs between layers, the rocks in the hanging wall are generally older than the rocks in the footwall.

How to construct a sedimentary column

It is not much use having a list of lithological units and not be able to put them in any relative order. This is when the building of a sedimentary column becomes very useful and should be done as soon as possible, as time in the field is usually limited. Recalling the exercise using the aerial photographs, we picked out areas that are the least deformed and the best exposed and constructed several sedimentary columns at those locations. After having obtained a set of sedimentary columns in the area of Camarasa (using a scale of 1:500 and 1:1000), they can be correlated according to their environment. Any environment from one sedimentary column that matches the environment of another sedimentary column is likely to be a match. For instance, we determined that the rocks in the north east are lagoonal carbonate rocks, Cretaceous of age followed by gypsum and we could correlate these rocks with rocks having the same fossil content and sequence located in the north west.. Of course, this sedimentary column only includes the general characteristics of the region. Some local phenomena are not included. In the end we constructed a final sedimentary column with a scale of 1:5000 that demonstrates the geological history of sediment deposition in the Camarasa area.

. However, there is more to field mapping than recording the types of rocks in the area. Nearly always the lithological units are folded and deformed and can even be repeated due to intense deformation. This is when the recording of the orientation of the bedding of the lithological units becomes useful.

How to construct profiles

Using profiles it is easy to understand the complex geological structures in the Camarasa area, and we constructed several profiles at different angles for clarity. A profile is constructed by transferring the measurements on the map by their strike to the line representing the cross-section. For us, the maximum distance between the place of the measurement and the profile was about 200m. However, this does not automatically give an accurate representation of the geological structures the profile crosses. Using field sketches the profile can be constructed much more accurately, because they can give a general idea of the structures present which can be accentuated in the profile. Many other corrections can of course be made in order to construct an accurate profile (e.g. corrections for height and foldaxis). However, the contibution of these corrections were so small that we did not use these for making the profiles.

Results

General introduction

In order to avoid tedious descriptions of the whole fieldwork area on a general basis, the region has been subdivided into zones. Each zone is defined by its characteristic succession of lithology and / or by its characteristic structures. Furthermore, each zone is bounded by either an unconformity, a fault, or less often simply by a normal contact. In part I, the lithology is descibed and in part II the structures within each zone and the boundaries between each zone are descibed. See appendix III, the zone map, for reference when the lithology and structures in each zone are described. Also the other maps (fact, field and interpretation map) are shown in this Appendix.

Part I - The lithology/tectono-stratigraphy in the Camarasa area

Appendix I contains a general stratigraphic column of the entire area and several detailed sections (i.e. local stratigraphical columns) which contributed to the construction of the general stratigraphic column. References are made where appropriate.

Table 1, the characteristics of each zone in terms of lithology, age and paleo-environment

	Lithology	Other observations + age	Paleo-environment
Zone A (see detailed section A)	Deposits are mainly calcareous rocks. There is an alternation of wackestone to packstone to grainstone. Further down hill there can be found more wackestone but which is greatly dolomised. Then a thick mudstone bed is exposed, followed by a grainstone and more mudstone beds.	The grainstones are often ooidal. Some beds are rich in fossils. Fossils such as rudists, oysters, miliolids and orbitoides are quite easily found. The fossil content indicates that these calcareous rocks are from the late Cretaceous. The younging direction was found to the right of the river Segre separating zone A in the north. From the cross-bedding found, the younging direction is uphill (i.e. northward).	Mostly edge – inner shallow platform.
Zone B (see detailed section E)	These deposits are mainly gypsum with a localised dolomised mudstone bed in it. Zone B in the east contains large blocks of	The gypsum seems to be deformed everywhere. Sometimes the gypsum even shows a schistosity indicating heavy deformation. There is no	Probably inner shallow platform – gypsum suggests high evaporation rates and a shallow water environment.

	mudstone, although some of it is dolomised, the larger ones are not. In the west, the large mudstone blocks are absent, but instead an igneous intrusion can be found. The dark minerals suggest it is a dolerite.	good evidence for a younging direction but as the gypsum is located below zone A, it logically would be older, probably Triassic of age.	
Zone C (see detailed sections B,C,E)	Zone C is characterised by the alternation of several siltstone beds and a thick mudstone bed and some thinner ones. In between there is often gypsum. The siltstone in the northern part of zone C is yellow coloured. In the southern part of zone C in the east, it is red coloured. In the southwest, there are 3 thick mudstone beds; however, across the river only 2 emerge (including the one with the thin layering).	One particular mudstone bed is very characteristic as it contains layering that progressively gets thinner. Near the road at zone C in the east, the mudstone contains isoclinal folds in this layering. This is also seen in the southwest and in zone G. The gypsum seems to be heavily deformed. The younging direction is northward as cross-bedding in the siltstones suggest. No fossils were found.	Inner shallow platform? / fresh water lake environment? Silt beds containing cross-bedding suggest river influence – clastic environment
Zone D (see detailed sections B,D,E)	This zone contains a grainstone bed (significantly dolomised) followed by a conglomerate bed. In the east, both eventually disappear eastward. What follows is a bed of red siltstone often containing gypsum. What follows are some thick gypsum beds and lastly there is an alternation of thin yellow coloured siltstone beds. The grainstone bed is not	The fossils in the grainstone (although dolomised) can be identified as nummelites, alveolinas, and miliolids. Thus, this means that the lithology in zone D is late Eocene. The younging direction in the east can be found to be southward as determined from the cross-bedding of the siltstone beds. In the west, however, the younging direction is northward, as determined from the small-scale troughs found. The	Edge (grainstone) to clastic environment & high evaporation rates (gypsum) of salt?/fresh water? Lastly, there are river dominated silt deposits that contain bidirectional cross-bedding, low energy environment, probably tidal floodplain. Grainstone pebbles in the conglomerate suggest that it probably comes

	found in the west but instead there is a thick conglomerate bed.	conglomerate is most likely a river deposit / alluvial fan.	from the grainstone bed, which has been eroded.
Zone E (see detailed sections C,E)	In this zone there is only a very thick conglomerate bed.	The conglomerate is characterised by small to very large pebbles. The pebbles are mostly calcareous, some are mudstones and others pack or grainstones. The packstones particularly only contain alveolina fossils. This suggests that this conglomerate is probably late Eocene – early Oligocene. The conglomerate of zone D does not seem to contain large pebbles, whereas the conglomerate of zone E does.	Alluvial fan deposits. Debris eroded by water from a higher located region (mountains).
Zone F	This zone is entirely a pack to grainstone containing an abundance of fossils.	The eastern part of this zone is dominantly a miliolid packstone and is found nowhere else in the area. The western part of the zone also contains echinoid needles and bryozoans. It could be said that these two parts hardly relate to each other; even the orientation of the bedding is completely different. The central hill proves to be heavily deformed as well. Evidence for this are the many faults and fractures in the rock. Age of this zone is probably Eocene-late Eocene. It is speculative whether this zone correlates to the grainstone found in other areas.	Edge/shore face moderate to high energy environment. Miliolids packstone also suggests a hypersaline environment.
Zone G	This zone features a	Age of most of the zone is	Already discussed

	repetition of the grainstone and mudstone layers discussed in zones C and D. Particularly in the south of zone G, there is a small exposure of grainstone containing rudists.	probably late Eocene, except for the outcrop in the south, which proves to be late Cretaceous regarding its fossil content. The repetition of the distinct mudstone and grainstone layers clearly is a tectonic structure (see 'structures').	

Part II – Structures and Profiles

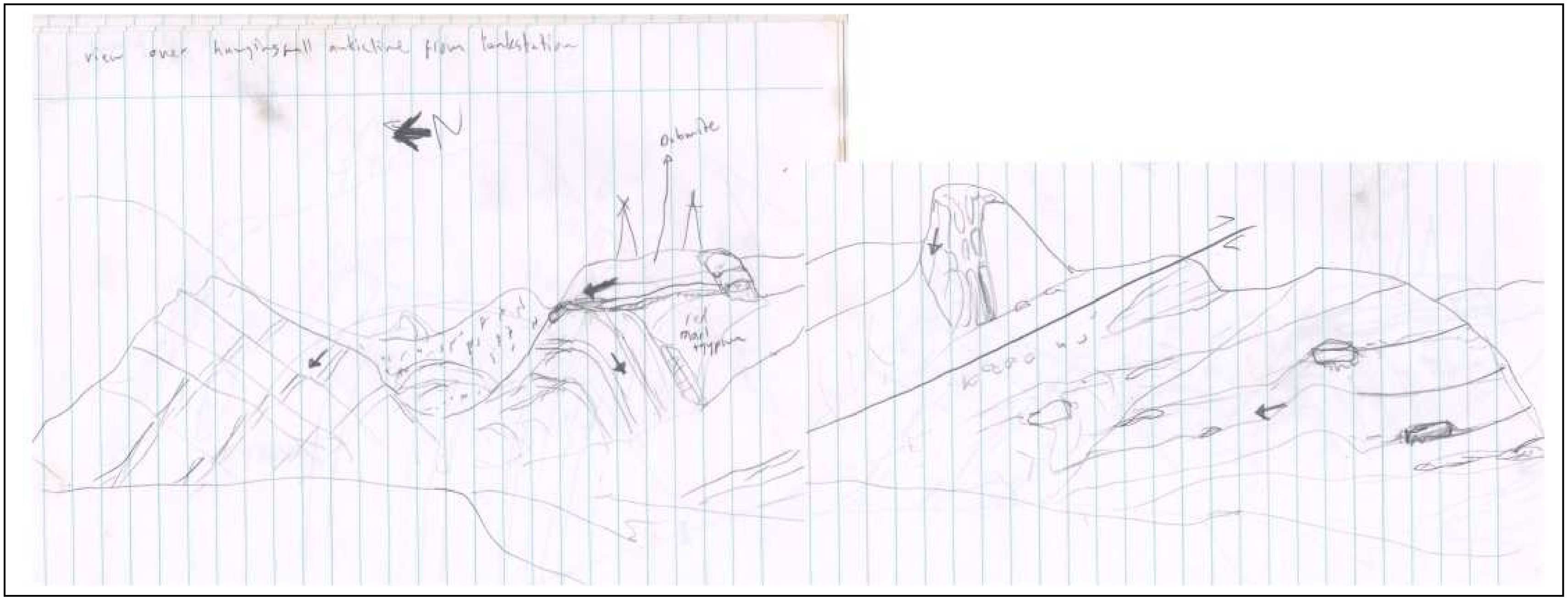
The contacts between the different zones were studied very carefully. By looking for evidence, a choice between the three types of contacts, defined in the Introduction, was made.

Zone A and zone B do not show a clear boundary in terms of erosional surfaces or a fault contact. This is also illustrated in the sedimentary column of the whole area. Gypsum and carbonate rocks are bounded by each other. No gypsum fragments of zone B can be found in zone A. Of course, this does not mean that there is no angular unconformity. In many cases, evidence for small grains of a layer in the layer above is quite hard to find. Nonetheless, we could only define the boundary between zone A and B as a normal contact, since no evidence was found for an angular unconformity or a fault contact.

One special feature of zone A should be given here. In the northwestern part of the study area, the carbonate rocks showed some serious changes in orientation in the valleys, which clearly visible in the field. This was not only an effect of erosion by the rivers, because the rocks were not continuous, but some discrete blocks were evident. This can explained by the presence of faults in these valley that offset the carbonate rocks.

On the contrary the contact between zone A and B, zone B and zone C shows a very clear boundary. This can be seen in the western and the eastern part of the area on the interpretation map. A thrust fault is given as the contact between the zones. Evidence for this thrust fault is the occurrence of a hanging wall anticline in the gypsum layers near Camarasa. This is illustrated in figure 1

Figure 1, Sketch of the hangingwall anticline made from petrol station (point 7.14 on field map)



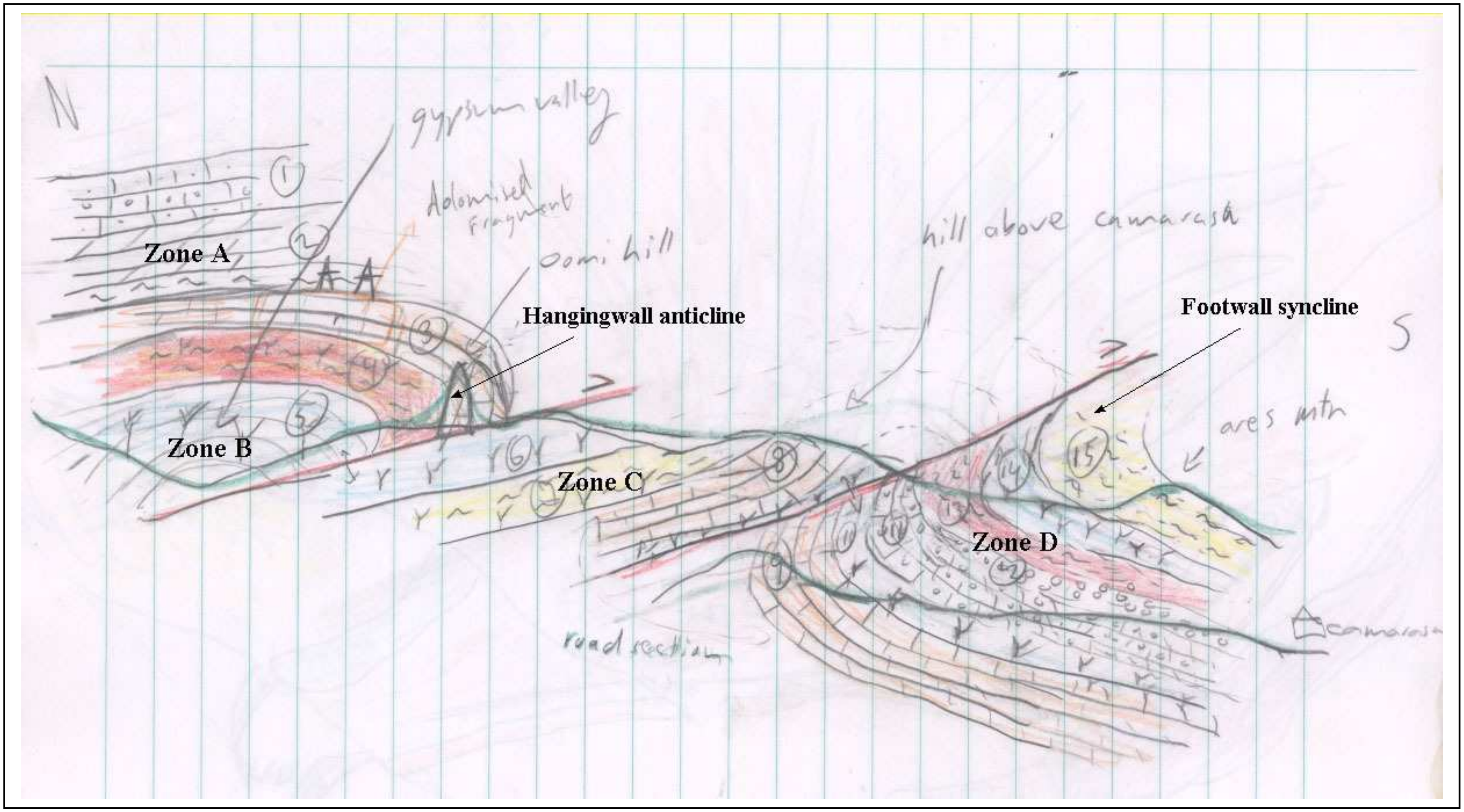
Further some blocks of mudstone (see interpretation map) occur in the gypsum of zone B, although only in the eastern part of the study area. These mudstone blocks can hardly be correlated to any layer in the surroundings. Therefore, the only way to explain this phenomenon is a thrust fault that transported these blocks from an area, positioned far away from the studied area. Finally the gypsum layers at zone B show in many cases schistosity. This is an indication for deformation. An angular unconformity between A and B is therefore hardly possible, because in that case the gypsum layers would hardly exhibit schistosity.

As said in the lithological part of the results section, zone B contains a dolerite body in the western part of the fieldwork area. No metamorphic phenomena, like contact metamorphism, are visible. The only way to explain the presence of this body is also by a thrust: the thrust transported (a part of an) igneous body that was already crystallized before it was transported. So the thrust fault in the eastern part of the area continues in the western part of the study area.

The boundary between zone C and D is also characterized by a thrust fault. Only good evidence of this thrust fault was visible in the eastern part of the fieldwork area, near the village Camarasa. On both sides of the thrust, a sharp difference in orientation of the layers is visible. Zone D exhibits layers with a dip direction to the south, whereas zone C exhibits layers with a dip direction to the north. At the contact between these layers, there is no gradual change: on the contrary the dip of the layers increases and the layers are positioned almost vertically at the contact. This situation can only be understood by a fault that cuts through the two different layers (see photo on front page).

The layers in Zone D near Camarasa form a footwall syncline. Evidence for this type of fold is found southeastern from Camarasa. A sketch was made of the geological situation. This sketch is given in figure 2

Figure 2, Sketch / geological profile of thrusts in east



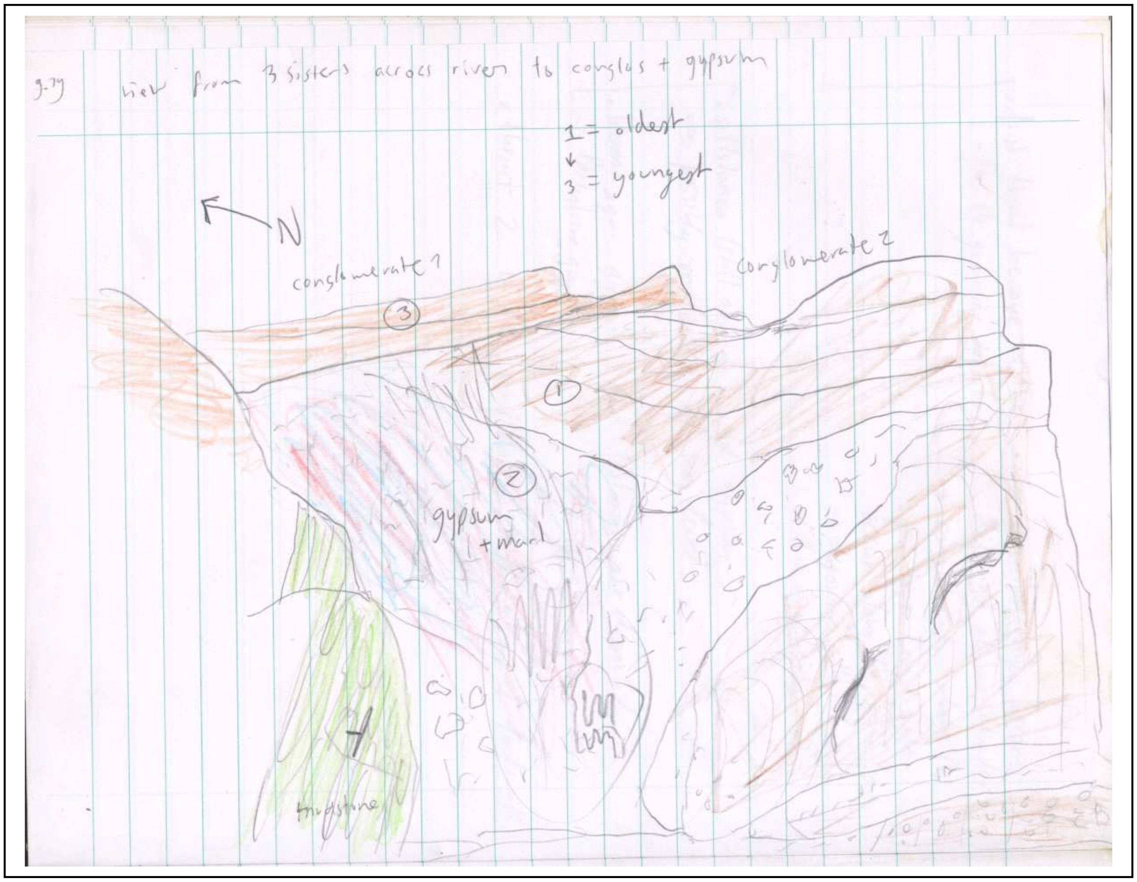
Further evidence of the footwall syncline was the gradual change in orientation of the layers in zone D from the boundary with zone C. Finally, fault gouge was visible between the contact of the two zones. This is illustrated in the sedimentary column of the whole area. In this sedimentary column between the gypsum layers (green colour) and the grainstone layers (light brown colour), conglomerate deposits occurred. These deposits were interpreted as fault gouge, because the thickness was varying. Detail section B will give further inside in the contact between these layers.

On the basis of the two predicted thrust faults in the area, in combination with the measured orientations of the layers, a profile was made through the eastern part of the area. This is given in Appendix II. The two thrust faults are given a red colour. The thrust fault are related by each other by a floor thrust. This floor thrust can also be seen in the ECORS profile and is an important phenomenon in mountain belts.

Collecting evidence for a thrust fault between zone C and D in the western part of the region was far more difficult for than for the eastern part. This was mainly due to the fact that the exposures were less clear than in the eastern part of the region. In the eastern part of the region, a good road section was present. These sections contained important evidence (e.g. fault gouge) for the thrust faults in the region. Because the evidence for a thrust fault is low in the western part of the region, no thrust fault is drawn on the interpretation map in appendix III. A profile is made for the western part of the region, including only the thrust fault at the contact between zone B and C.

The layers in zone D and zone E both consist of conglomerates. They have a quite similar composition. They consist of large pebbles (diameter till 50 cm) of grainstone with alveolina and miliolids. Further, some sandstone is also included. The only lithological difference is that the conglomerates in zone D have smaller pebbles than the conglomerates in zone E. Besides this lithological structure, there is a clear structural difference, illustrated in figure 3 This sketch is made for the contact between the conglomerate layers near the bridge over the Segre in the southwestern part of the area. It is clear from the sketch that the two conglomerates of zone D and E show different orientations with a contact that can consequently be considered as an unconformity.

Figure 3, unconformity between conglomerate layers in zone D and E near river Segre (point 9.19 on fieldmap).



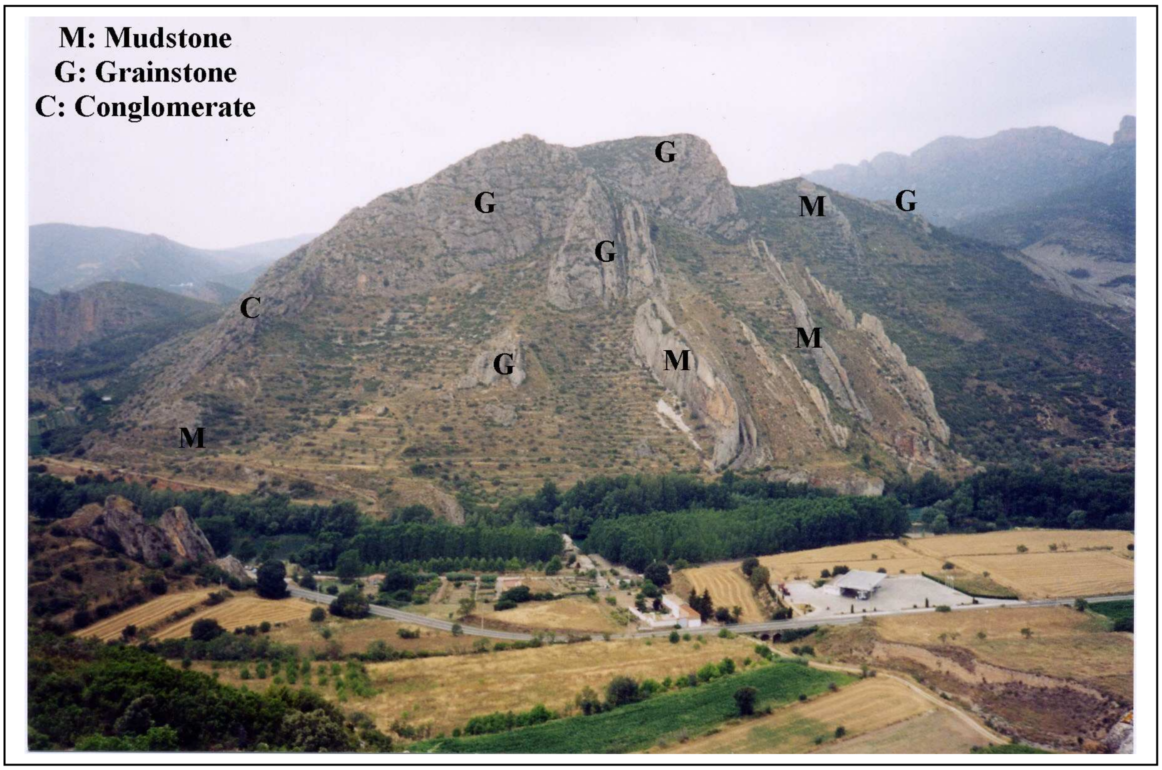
Zone C in the southwestern part showed a clear unconformity with zone E. Gypsum grains of zone C were found in zone E, which could be used as good evidence for the unconformity. Not enough evidence was found to decide if an unconformity is also present at the boundary with zone F. Evidence for the other boundaries of zone F was not also found. Therefore a normal contact was drawn on the interpretation map.

Zone C in the southwestern part of the region shows three resistent layers, the so called 'Three Sisters', already described in the introduction. The composition of these layers is given in detail section B. It is clear that the three layers have each a distinghuishable composition. The most eastern layer of the Three Sisters shows isoclinal folds, that can be correlated with the isoclinal folds in the road section near Camarasa. The two eastern layers reach each other at the top of the mountain. The contact between these two layers was not studied and therefore no clear statement can be given for this contact. A final special feature of the Three Sisters is that only two of the three rocks can be seen on the other side (northern) of the river. The middle layer of the Three Sisters was not found at the northern side of the river. It is quite difficult to understand this phenomenon.

Sant Salvador and surrounding area

The last part of the area, that should be discussed, are the layers in zone G around the Sant Salvador mountain. Looking at the interpretation map, zone G shows a repetition in a grainstone layer, rich in alveolina and miliolides forams and in a mudstone layer. Figure 4 is a photo of Sant Salvador, clearly showing the repetition of the grainstone and mudstone layers.

Figure 4, Photo of Sant Salvador taken from a hill in zone C to the north of Camarasa (called Oomi hill)



The repetition of these layers occurs three times. This phenomenon can only be understood by the presence of three thrust faults that result in the repetition of layers. Based this idea, three profiles were constructed in order to get a better impression of the complex structure of the Sant Salvador (see again appendix II).

By looking at both these three profiles as at the interpretation map, it is clear that the three thrusts at the Sant Salvador are foreland dipping in the northern side of the Sant

Salvador and hinterland dipping at the southern side of the Sant Salvador. Futher, the interpretation map shows that a fold must be present in the whole Sant Salvador, that results the change in orientation of the thrusts and the mudstone and grainstone layers.

It is quite difficult to place the three thrust of the Sant Salvador in the context of its surroundings. The thrust between zone C and D in the eastern part of the study area seems to end at the western side of the river Segre, near the Sant Salvador mountain. Then, the three thrusts of the Sant Salvador appear. The contact between the three thrusts of the Sant Salvador and the thrust between zone C and D could possibly be a fault contact.

One final special feature in zone G was the presence of Cretaceous rocks in the southwestern part of this zone, because of the presence of rudists in these carbonate rocks. These rudists showed extended structures. Further, the carbonate rocks are folded, which can be seen on the fold axis, drawn in the interpretation map. The presence of Cretaceous rocks, surrounded by the mudstone and conglomerate rocks of Late Eocene age, is of course a special phenomenon in this region and is treated in the discussion section.

The layers in zone D around the western part of Sant Salvador show an interesting structure. Mainly conglomerate rocks change in orientation. If you compare the strike/dip measurements of zone D on the fact map it is clear that going from north to south along the Sant Salvador Mountain, the dip direction of the conglomerate layer changed from east to northwest (e.g. compare on the fact map the orientation of point 9.17 with point 2.13). Near the contact of zone G, no evidence was found for a thrust fault. On the other hand, no evidence was found for an unconformity, because no gypsum grains of zone D were found in the conglomerate layer of zone D. But the occurrence of conglomerates indicates that an erosional phase must have happened. Therefore the contact between zone D and G is considered as an unconformity contact.

Summarizing the results about the structural geology of the study area:

- Two clear thrust faults are dominant in the study area: one fault in the north, positioned between zone B and C, and the other thrust fault, positioned between zone C and D in the eastern part of the area that makes some change in orientation at the Sant Salvador mountain. The fault between B and C can be extended to the western part of the area, but there is hardly any evidence for the fault between zone C and D in the western part of the area. All the faults are related by each other by a possible floor thrust, characteristic for a mountain belt.

- A well developed hanging wall anticline is present in zone B and a footwall syncline is present in zone D, both in the southeastern part of the study area.
- Around the Sant Salvador mountain (mainly western side), an interesting change in orientation of the conglomerates layers is visible.
- The gypsum layers in the northern part of the area show a great deal of schistosity.

Discussion

General introduction

The discussion that will follow will be subdivided in two parts. First of all the important geological phenomena in the region will be discussed, including the dominant lithology and structures of the region. After this first part, a geological history follows, that explains the formation of the important geological features in the study area

Regional Interpretion

Based on the lithological and structural results, described in the previous section, a description can be given about the important geological phenomena, that dominate this area, which is part of a large foreland. This was also one of the aims of the study.

The study area is mainly characterized by sedimentary rocks; the most important rock types are carbonate rocks (grainstone-mudstone), gypsum, siltstones and conglomerates. The age of the rocks is varies from Triassic till Late Oligocene. The gypsum and carbonate rocks represent mostly edge – inner shallow platform and lacustrine environments. Fossils, like miliolids and alveolina, are an indication for this. The siltstones represent river dominance in the region with clastic sediments. Finally, the conglomerate rocks, which are quite abundant in the southwestern part of the region, represent periods of erosion after/during tectonic activity. One of the best examples is the carbonate conglomerate around the Sant Salvador, with pebbles rich in alveolina and miliolides grainstone. This means that the grainstone, rich in alveolina and miliolides, must have been uplifted during tectonic activity. After/during tectonic activity, erosion becomes dominant. It is the erosional material, that is a testimony of this previous uplift.

However, conglomerates are not the only indicators of tectonic activity that must have happened in this region. The region shows many fault and fold structures. The hinterland dipping thrusts are abundant throughout the whole region. These thrusts caused older rocks to be surrounded by younger rocks. The large cliffs in the north, composed of carbonate rocks (zone A), are from Cretaceous, whereas the grainstone and conglomerates are from Eocene age and younger. After the Eocene grainstone and late Oligocene siltstones were deposited, a thrusting period resulted in the transport of Cretaceous carbonates and Triassic gypsum from elsewhere to this region, forming the large cliffs in the northern part of the study area.

This thrust, between zone B and C, is present at both sides of the river Segre. On the other hand, the thrust between zone C and D is only present at the eastern side of the river Segre. Different possible explanations can be given for the absence of the thrust between zone C and D at the western side of the river Segre. First of all, as already said in the Result section, the western part of the study area showed less well exposed geological structures and therefore it is possible that although the thrust is present, hardly any evidence can be found for this thrust. Secondly, it is also possible that the thrust on the eastern side of the river becomes a blind thrust at the western side of the river. This means that the thrust is still present, not at the earth's surface, but deeper in the crust. Blind thrusts are quite common and can therefore explain the absence of the thrust between zone C and D in the western part of the study area.

The thrusting produced quite important geological structures in this area. In the eastern part of the area, a hanging wall anticline and a footwall syncline were formed by the activity of the thrust. Secondly, the thrusts resulted in the repetition of layers, that can be found in the Sant Salvador mountain. Finally, the presence of the Cretaceous rocks in the southwestern part of the Sant Salvador can also be explained by thrust movement. It is the same idea, as already given about the formation of the large carbonate cliffs in the northern part of the area. The only difference is that erosion must have occurred and further thrusting, isolating this Cretaceous rock from the other Cretaceous rocks.

The final question is by what effect this thrust activity was accomodated. The answer lies at the material properties of gypsum. It is clear from the sedimentary column, given in appendix I, that all the thrusts occur at gypsum. Further, especially in the norhtern part of the region, schistosity was found in the gypsum layer, indicating that deformation has taken place here. So gypsum accomated the formation of the thrusts in the region, because it acted as a lubricant. All the rocks could slip over the gypsum layer. The thrust between zone B and C, containing a Triassic gypsum layer, even contains whole blocks of Cretaceous mudstones in the eastern part of the study area and dolerite in the western part of the study area. These rocks were not found elsewhere in the region and are therefore considered as rocks that have an origin away from this region. Further, the rocks around the dolerite did not show metamorphic conditions, which is another indication that the dolerite body must have come from elsewhere. The presence of mudstone blocks and the dolerite body in the gypsum indicates that a whole section of rock can be torn away from its original location and can be incorporated in the gypsum and transported to other places.

The gypsum layers that are quite abundant in the study area, were very important for the formation of the thrust faults in this region. Without the presence of the gypsum, the actual geology would be completely different.

The geological history of the Camarasa area

The initial setting of sediment deposition is at around early Eocene (~36Ma) when the environment is the southern part of the Pyrenees is still marine influenced. According to the general stratigraphic column (see appendix I), it was the thick mudstone beds that were deposited first followed by some gypsum and fluvial redbed sediments. However, the mudstone shows a distinguishable feature that is not seen in any other type of rock, which are the isoclinal folds. This means that straight after the deposition of this sediment, there must already have been tectonic movement. It is possible that uplift and compression occurred and the mudstone was subjected to these forces. The extend of uplift is, however, arguable because no mudstone conglomerates were found. The next deposit tells us that there must have been subsidence afterwards, or relative sea level rise.

During the next depositional event grainstone was deposited. The grainstone again hints at a shallow marine environment close to the edge of the inner shallow platform. It is possible to deduce from the subsequent conglomerate deposits that an enormous amount of grainstone must have been deposited. Additionally, this must have required a great deal of accommodation space in the basin. Noticeably, as seen on the field map (appendix III), there is much grainstone found in the southwest of the area. It is probable that this sediment was deposited around the same time as the other grainstone deposits elsewhere in the area. Nevertheless, in the east only a couple metres thick grainstone remained (see appendix I, the general stratigraphic column) and its top surface is marked by an unconformity. This again means that after the grainstone was deposited, there must have been another period of tectonic uplift, this time uplifting not only the grainstone but also the previously deposited mudstone. This may well be the moment when the antiformal stack, Sant Salvador, was first formed. A detailed analysis of Sant Salvador is found in the next section.

During the next episode of erosion, thick conglomerates were locally deposited as alluvial fans. There is no hint of sub-aqueous deposits thus these conglomerates were deposited on land. Additionally, these deposits contain very large pebbles up to half a metre in diameter, thus transport of erosion material occurred over a small distance. It may be important to point out that these periods of deposition, uplift, and erosion take a considerable amount of time maybe up to 6 million years which means that this is no longer Eocene, but middle Oligocene (~30 Ma).

Noticeably, in the west (see appendix I) there is a distinct contact between two different types of conglomerates, where one does not contain any large pebbles. This contact between these two types of conglomerate is an angular unconformity (see results part 2 and appendix I). This means that there were two periods of erosion instead of one and that during the second period of erosion the transport of material occured over a larger distance and that the material from the previous conglomerate deposits was in effect reused.

It would be a reasonable assumption that the time it took to deposit these conglomerates, would be around 3 million years, so that the next sediments were deposited during the late Oligocene (~27Ma). These sediments must be, according to a thesis on the *Cenozoic tectonic evolution of the Iberian Peninsula*, terrestrial deposits and the gypsum therefore lacustrine[1]. Besides gypsum deposits, there are also fluvial red bed sediment deposits in zone D particularly, and clean yellow fluvial siltstone deposits containing bidirectional cross-bedding (see results part I).

Subsequent increased tectonic activity, that uplifted the Pyrenees to a state as we now know it, caused all the deposits to become involved in a major fold and thrust complex. It is also important to note that during this compression phase, erosion also took place and it must have been quite significant. A major thrust from the north compressed the Paleogene deposits and even slit over it due to the Triassic gypsum it is positioned on. Note that in the Camarasa area the rocks transported by this thrust were determined to be Cretaceous of age (see results part I). There is evidence that the trusting covered quite a distance because of the size and curvature of the hanging wall anticline of the thrust and of the footwall syncline. It is reasonable to suggest that the second thrust in the south was created by the pressure exerted from the northern thrust and thus formed roughly at the same time. Noticeably, it seems that the northern thrust in the east propagated further south than the one in the west. This is a typical example of a tear fault (but a very large one). The movement of the thrust in the west was simple obstructed by the presence of a dolerite body in the gypsum and likely by Sant Salvador itself.

This covers the general geological history of the greater part of the area, however in the centre of the region there is positioned a geological complexity that is called Sant Salvador. The next section will attempt to explain how it got there and how it was formed.

[1] http://www.geo.vu.nl/~andb/iberia/thesis/chapter4/Chapter4.pdf

Sant Salvador – a possible geological history of its formation

It was discussed that during the lower Eocene an episode of uplift/compression occurred that involved the mudstone and grainstone deposits. This must be already the critical moment when Sant Salvador formed. This is because the subsequent deposits, i.e. the conglomerates, cannot be found on the mountain! Noticeably, Sant Salvador is not just any mountain containing folded beds, but represents an antiformal stack. Evidence for this can be found by the repetition of the mudstone and grainstone layers up to three times. The thesis on the *Cenozoic tectonic evolution of the Iberian Peninsula* suggests that "break-back thrusting and increased thrust rate [Puigdefàbregas *et al.*, 1991] cause rapid building of an antiformal stack (within ~1Ma), increasing the relief significantly, which leads to coarse alluvium entering the foreland basin from the north."[2] Thus, an antiformal stack was formed and was subsequently partly eroded, the erosion material being the conglomerates at the foot of the Sant Salvador (in zone G). The variation in orientation of these conglomerate layers, shown in the second part of the Result section, is the result of later tectonic activity

However, there is more to Sant Salvador than being just an antiformal stack. In fact, Sant Salvador had to endure the next 36 millions years of uplift, compression, thrusting, and erosion. Therefore, much must have happened to it. This is clearly visible, because it seems that the horses of the entire antiformal stack have been folded with a fold axis roughly pointing southeast, which can be derived from the different orientations of the layers on the interpretation map. However, even the mudstone and grainstone beds in Sant Salvador itself experienced folding, faulting, and displacement. The outer mudstone bed seems to be completely folded isoclinally. In addition, the vertical standing mudstone beds on the eastern slope seem to be folded on itself or seem to end suddenly. However, the most striking aspect of Sant Salvador is that during the thrusting that occurred after 27 million years ago the thrust in the north of the area seems to have rotated the mountain anti-clock wise. Evidence for this is the fold axis of the folded horses. If there was no rotation then the fold axis should point southward. If the thrusting comes from the north, the thrusting would be either hinterland dipping such as both thrusts in the east of the area, or foreland dipping which means that the horses of the antiformal stack of the Sant Salvador have moved over each other, which may be the case. Other evidence pointing to the rotation and deformation of the Sant Salvador is the offset in the Northern thrust at zones B and C in the east and at zones B and G to the north of Sant Salvador. This proves that the Sant Salvador is obstructing the thrusting

[2]http://www.geo.vu.nl/~andb/iberia/thesis/chapter4/Chapter4.pdf

from the north and as a result it got deformed and rotated. In addition, in the east of zone G near the river Segre, the mudstone layer shows to be bend southwards which could have been caused by the rotation of the mountain. Nevertheless, it is very important to point out that the folding and thrusting would not have been possible to this extent had there not been any gypsum. And in fact there is gypsum found on Sant Salvador, which is the gypsum that was deposited after the mudstone during the early Eocene.

There are two last features to discuss which is the presence of a dolerite body in the west and the '3 sisters' in the southwest.

The dolerite body in the west

This intrusive rock is in fact not an intrusion as already mentioned in the results section part II. It was brought to the surface probably during the later thrusting that occurred after 27 Ma ago. Thus, it is not puzzling why it is there, but what it caused. When observing the strike and dip of the cretaceous rocks in the north above the dolerite body, it is striking to realise that the strike and dip are not the same everywhere. Moreover, there is a considerable difference measured on one side of a valley compared to the other side of the valley. The reason is simply because the force it took to push the dolerite body to the surface caused the northern thrust to bend and break and what resulted may look something like tear faults in the thrust. This caused the cretaceous beds locally to change orientation. In fact, each valley in the northwest is something similar to a tear fault but not laterally but vertically (i.e. the faults came about by vertical breaking due to the presence of the dolerite body underneath).

The Three Sisters

The southwestern part of the region, dominated by the 'Three Sisters', is difficult to explain from the results of the investigation. There is no conclusory evidence found that the 3 mudstone layers may in fact be the same, since the three layers all seem to have a distinghuisable composition. All that can be said is that they are made up from the same mudstone found in Sant Salvador and elsewhere. That is, on one of the mudstone beds of the 3 sisters isoclinal folds can be seen and all beds seem to be made up of thin mudstone layers. Another observation made was that only 2 mudstone beds can be found on the other side of the river. Because more details about the 'Three Sisters' were not investigated in the study, more cannot be said about the 'Three Sisters'. More research will be necessary in order to understand the 'Three Sisters' in greater detail.

Conclusions

The aim of this study was to investigate the important geological phenomena, in terms of lithology and structure, that occur in the foreland of the Pyrenees. This was done by mapping an area of certain squared kilometers big in the northern of Spain and deducing from these results the geological history.

- First of all the studied area contains rocks that were deposited in situ from early Eocene (36 Ma) till Oligocene (27 Ma). These rocks are quite abundant in the southern part of the region (zone C, D, E). An important regression of the relative sea level can be derived from the sediments. The Eocene deposits were dominated by edge - inner shallow platform carbonates (mudstone- grainstone), containing fossils like alveolina and miliolids. A tectonic phase must have occurred after the deposition of the last carbonates, because the subsequent deposites are mainly limestone conglomerates. Because of the large deposits of these conglomerates but the relatively thin grainstone layer (a few meters thick) that was found at the road section near Camarasa, much erosion must have occurred of the previous limestone layers. After the deposition of the conglomerates in the late Eocene, the environment remains terrrestrial with river deposits (siltstone) and lacustrine deposits (gypsum).
- Besides the relatively young rocks, that were deposited in the south, some older rocks do also occur, especially in the northern part (zone A). These are Cretaceous carbonates and Triassic gypsum. The rocks were not deposited here in situ, but were transported to this area by a thrust.
- Different thrusts were mapped in this study. The most important thrusts are the thrust between zone B and C, the thrust between zone C and D (only in the east) and the thrusts in the Sant Salvador mountain. All the thrusts share some commom properties. The most important one is that all the thrusts occur at a gypsum layer. This means that the gypsum acted as a lubricant. The best example of this behaviour can be found between zone B and C, where great mudstone blocks and dolerite blocks occur in the gypsum. These blocks do not occur elsewhere in the region, but where transported to this region by the gypsum.
- Thrusting has played a major role in this area and resulted in a complicated structural geology. Phenomena, related to thrusts, like footwall syncline and hanging wall anticlines were found in the eastern part of the area. Further, the thrusts in the region were all hinterland dipping except the ones located at Sant Salvador. The hinterland dipping thrusts became active after the deposition of the

last terrestrial sediments in the late Oligocene (27 Ma), but the thrusting of Sant Salvador happened earlier.

- The Sant Salvador thrusts already became active in the early Eocene, after the deposition the of the last grainstones, at the same time when the limestone layers were uplifted and eroded. An antiformal stack was produced with foreland dipping thrusts.The different thrusts produced a repetition of the mudstone and grainstone layers. Besides the thrusts, a general fold structure also developed with a foldaxis roughly pointing to the southeast, and many smaller ones each pointing in other directions. This can possibly be explained by rotation of the mountain.
- Although some interesting geological phenomena could be explained by the study, some unanswered questions still remain. First of all, the fault between C and D does not appear on the western side of the Segre. A blind thrust could be an explanation for this. Perhaps geophysical research could indicate if a blind thrust is indeed present between zone C and D at the western side of the Segre. Secondly, the southwestern area is mainly unsolved. More attention should be given in a further study to all the contacts between the different rocks. Finally, the Sant Salvador still remains a very complicated structure. More information about the contact with for example the fault between zone C and D, should give a better understanding of the place of the Sant Salvador in the whole region.

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