DRAGONSTONE 2

ITN-S2S-FUTURE SUMMER INSTITUTE

1. Introduction

Dragonstone 2 was held in Northern Spain from 25 August to 10 September 2021. The main organisers of the workshop were the University of Geneva (UNIGE) and the University of Rennes 1 (UR1). The Summer Institute leaders were S2S experts from different European universities: François Guillocheau (UR1), Sebastien Castelltort (UNIGE), Cécile Robin (UR1), Jean Braun (GFZ), Alex Whittaker (Imperial) Luis Valero (UNIGE), and Thierry Adatte (University of Lausanne). The aim of Dragonstone 2 was to complement Dragonstone 1 held online from 11 to 15 January 2021, which had delivered at the onset of the program the essential concepts and big picture overview of the scientific objectives and power of the S2S approach through a combination of class-room lectures, essential literature reviews, computer modeling hands-on and experiments to manipulate concepts. On the other hand, the focus of Dragonstone 2 was on field examples and excursions in the southern-Pyrenees in Spain: from alluvial fans of the northern Tremp basin all the way down to deep basinal turbidites of the Zumaya area, following marker timelines such as the PETM, the EECO and the MECO. These field excursions were combined with presentations by the PIs and the representatives of partner organisations, and the final four-day course focus on seismic geomorphology and sequence stratigraphy with a specific focus on particulate gravity flows in source-to-sink sedimentary systems. Dragonstone 2 gathered 32 participants, including 14 ESRs, instructors, representatives of beneficiaries and partner organisations as well as external participants.

ESRs and PIs during Dragonstone

The summary of activities per day

In this section we present the activities that took place during each day of the training programme, summarized by ESRs.

Day 1: 25 August 2021

by Melanie Kling and Amanda Wild

The objective of day one was to familiarize the ESRs with basic approach of landscape and outcrop interpretation. The key point was for researchers to be pragmatic: before jumping to conclusions and interpretations one should first consider multifaceted evidence and consider alternate possibilities. Researchers were shown the tools to identify where they are within the sedimentary record (continental or marine) and began to discuss different internal and external signals that can impact the sedimentary record. To practice our skills on day one, ESRs looked at a alluvial fan outcrop, paleo-channels, and marine shelf deposits.

<u>Stop 1: Montserrat</u>

ESRs began by drawing and describing the stratigraphy. Montserrat consists of vertical and lateral variations of coarse grained facies interbedded with fine grain vegetated material. Sebastien explained that Montserrat is an alluvial fan deposit that formed during the Bartonian (41.2 to 37.8 Ma) that was sourced from the SE Catalan Coastal Ranges. We discussed a possible progradation with fore-stepping and back-stepping cycles that could cause the alternations between the coarse alluvial fan deposits and the fine sand/limestone/marine shelf deposits.

We then began a broader discussion regarding the on disentangling climatic, tectonic, and eustatic triggers and signal propagation. A theoretical road path as to how one would go about disentangling the origin of a signal within a foreland basin was discussed as: 1) calculate the flux, 2) date the sequences (magneto-stratigraphy), 3) quantify subsidence/accommodation (can indicate uplift), 4) interpret backwater distance of eustatic influence, 5) identify climate cycles (eg: eccentricity), 6) consider thresholds (mean precipitation relative to extreme events), and 7) discuss possible decoupling of the marine and alluvial responses.

Sébastien Castelltort with Monserrat in the background

Stop 2: Road to Rellinars Continental

Approaching the first outcrop, we were instructed first to describe the facies, then identify biological component (foraminifera and bioturbation), and then identify larger structures and sequences (unconformaties, faulting, and stratification). After this one can make some inferences as to whether you are continental or marine, make additional measurements to determine flow direction, and make larger interpretations as the nature and formation of the outcrop.

After describing conglomerate facies (well rounded, clast-supported, elongated, 1-10 cm diameter, polymictic, sandy, bioturbated, imbedded roots, and red in color), and a finer grained (hydromorphic to calcareous) sandy soil facies, we identified the deposit as continental fluvial. The well-sorted clasts display imbrication in the east/north east direction indicating the flow direction. Further interpretation of the outcrop based on field observation fits a migrating (cut banks) and braiding (truncation of channels) of conglomerates with some concrete calcite layers (arid periods) incising into finer floodplain with lateral accretion.

After interpreting the outcrop further discussion was made on quantitative measurements that can be made or derived from the sedimentary record. For example, grain size and channel depth measured in the field can be used (through the shields equation) to estimate the paleo-slope. Paleo-slope calculations are a precursor to estimating paleo discharge and precipitation (which inherently can be used to derive velocity). Thus, under the right outcrop paleo-channel conditions, with some calculations you can better estimate the drainage conditions of the basin.

Stop 3: Road to Rellinars Marine

As we walked down the road, we transitioned from the continental deposits to shallow marine deposits. This was identifiable through a change in color (from red continental to grey-brown marine deposits), an abundance of shells, and an increasing diverse number of burrows. We discussed what the diversity and abundance of burrows can tell us about the environmental conditions (happiness index). The high abundance of diverse species indicate that the area was shallow with enough light with plenty of (but not too much) nutrients, indicating shallow marine shore face. The sandstone was well-sorted and, along with the presence of hummocky features, indicates wave dominant conditions. The well-sorted sandstone (due to wave action) that was brown in color (due to the weathering of iron rich carbonate) Francois pointed out as transitional facies that would make an excellent reservoir.

Stop 4: Overview

We ended the field day (before the bus ride home and evening scientific discussions) with an overview of the landscape. Here we saw continental sediments with blue marine lateral extensive and continuous (indicative of a low energy depositional system) layers on top. This connects to the braided fluvial system, as well as many fan (eg.Montserrat) and inter-fan areas in the surrounding landscape.

Day 2: 26 August 2021

By Caroline Fenske, Rocío Jaimes-Gutiérrez

The main objective of the day was to identify and understand the thrust and fold belt system in the Pyrenean piggy-back basins. The fold and thrust belt system we observed on this day in the Southern Pyrenees is restricted to the centre of the Pyrenean foreland basin (also known as Tremp-Graus-Pamplona basin). It is wider and more developed than in the other parts of the foreland basin. Its development starts with the propagation of stresses from the North to the South, from the late Cretaceous to the Paleogene. All the observed thrusts are joined at the base through a detachment level on Triassic layers. This interconnection creates the piggy-back basin landscape, the Tremp and Ager basins, with folds at the base of each thrust. From oldest to youngest, the sequence consists of the Boixol Thrust (San Corneli Anticline), the Montsec Thrust (Sierra del Montsec) and the Sierras Marginales Thrust (Sierras Marginales), creating anticlinal reliefs. After the end of this period, a reactivation of the detachment level is observed. This leads to the creation of out-of-sequence backthrusts during the Paleogene, for example the Morreres Backthrust and creating new basins like the Pobla basin in the Eocene. We observed this in the field, where we stopped at the Sierra del Montsec on the Ager Basin side, followed by the Tremp Basin and finally in the Pobla Basin.

Stop 1 and 2: Ager Basin

The Ager Basin is a synclinal basin between the Sierras Marginales and the Sierra del Montsec. At the Montsec thrust on the Ager basin side, we can observe intensive folding. The overturned Paleocene/Eocene transition outcrops in the area. The sequence consists of continental sediments, which are mostly red paleosols (Paleocene), to a transgressive episode of carbonate and sandstone marine/coastal layers (Eocene). The transgressive episode is marked by a change to grey colors, indicative of the reducing conditions. In terms of paleoenvironment, this indicates a transition from fluvial (depositing the red paleosols in the floodplains) to coastal and later marine then again to coastal. Possible hypotheses could be sea level variations (eustasy) or tectonic changes. In a source to sink approach, the sequence evolved down the sediment routing system, from the transport zone to the start of the sink.

Stop 3: Tremp basin

The Tremp synclinal is the oldest of all the piggy back basins of the system. It is between the Sierra del Montsec and the San Corneli anticline. It is filled by Paleocene and Eocene marine to continental sediments, with Cretaceous rocks at its base. The latter can be seen on the edges as chevrons. At these edges, a progressive unconformity is also observed in between the Paleocene and Eocene layers.

From the South to the North, there is a global thickening of the Paleogene sediments, but each individual bed is thinning in the same direction. This fan-like structure depicts more accommodation space to the North. At the same time, a facies transition is evidenced in the change from limestone to marls (finning of sediments down the basin).

Tremp basin

Stop 4: Pobla basin

It is the smallest and youngest of all three basins. It was formed during the Eocene after the reactivation and movement of the Morreres Backthrust. The basin is filled with Eocene to Oligocene sediments, but because of the folding (occurring between 100 Ma and 42 Ma), connected to the thrusts, an angular unconformity is observed between the underlying Cretaceous carbonates (at least 100 Ma old) and the Eocene sandstones (younger than 42 Ma). The conglomerates observed in the Pobla basin are the same age as the ones in the Tremp basin, but originate from different sources.

Day 3: 27 August 2021

By Iwan Setiawan and Lucas Valore

Stop 1: Figols Fm.

Our first stop is at the west of Tremp city. The objective in this location is to discuss the clay sampling techniques and tempestites. We saw a marls succession of Ilerdian age. It contains bioclastic clasts, this succession is equivalent to Alveolina Limestone (Eocene). In the first stop we talked mostly about the clay sampling for isotope analysis, presented by Rocio Jaimes (ESR#10). It is important to constraint the mineralogy (XRD, SEM, etc.) and the ages. For the dating analysis, there are 3 types of fossils that are importants. They are planktonic forams, benthic forams, and nannofossils. We can also analyze the paleooceanography conditions using those fossils, for examples: temperature of bottom sea water using benthic forams; temperature of surface sea water using planktonic forams. To the east, in the middle of marls dominated sequence we found a metre of bed of coarser grains deposits. It is characterized by erosive base, fine-medium sand, low angle cross-bedding (hummocky), wave ripples at the top, fining upwards sets and some shale layers that suggested multiple events. We had a discussion that it can be deposited by storms (tempestite) or turbidites or combination of both. Tempestite can be used to infer condition on climate and paleogeography (e.g. tropical storms). The sandstone that we found here is a great example of clean sand.

Figols Fm.

Stop 2: Montl lobat

Moving to the second location, our objective is to understand the prograding delta succession. Above the bioturbated marls, we found succession of sand bars that downlapped to the east. It includes cross-bedded sets (10-30 cm) form by dunes migration, thickening to the west. We also found conglomerates at the bottom and top of this succession. We can see the shallowing upwards trends, no wave and tidal actions, so we can interpret this succession as the prograding mouth bars of flood dominated delta. Directly above the delta we found fine-grained sequence rich in oyster's shells that could be interpreted as the deposits of mangrove environment. Moving laterally to the west, we found the succession of flood plain mudstone with patchy colors (mottled), root traces (pedogenesis) and eventually we get the channel deposits. In summary, we are more into fluvial realms (Montanyana Fm.) to the west which represents overall prograding trends.

Stop 3: Mont Lobat (panoramic view)

From this view point, we can see the anticline structure at the San Cornelli and interpreted the Boixols thrust just beneath it which also controls the Tremp basin to the south and the back-thrust to the north (Pobla basin). All the structures are plunging to the west by 10-20°.

We also had a discussion with Prof. Sebastien Castelltort about parasequences as well as the allogenic (external forces) and autogenic (internal dynamics) which influence their development. For determining allogenic influence, we could observe and be able to correlate the parasequences at a large scale (e.g. one basin to other neighboring basin) while for the autogenic in the case of delta, it happened more locally (e.g. lobe switching). We also discussed the quantification approach to assess this issue by using compensation time which requires height of a sedimentary body (h, e.g. median height of delta front) and sedimentation rate (SR).

Mont Lobat

<u>Stop 4: Badlands</u>

In this location we discussed more about the drainage systems rather than the outcrop itself because we can see the "miniature" of drainage systems model. Prof. Jean Braun explained how important is (1) river incision -> channel (advection), and (2) hillsope processes -> interfluve (diffusion) in the development of drainage or catchment system.

We also discussed about the soil creep which its rate is proportional to the slope. The rate of change in topography also proportional to the curvature (dome). He also explained the two important limiting factors in soil creep, (1) transport limited, which corresponds to the point where bedrock will emerge because there is no soil left at the surface to be transported, and (2) production limited, which corresponds to rate of conversion of granite to soil.

<u>Stop 5: Montanyana Point Bar</u>

Mirador del "point bar" Montanyana provides a great view of lateral accretion of point bars. We can clearly observed the oblique bedforms sets of sandstones. The bottom part of these sets consisted of coarser grains (bedload) and progressively changing to finer grains at the top (progressively changing to suspended load). The W-E direction of the lateral accretion gives an estimation of the river flowing at N-S direction which is at right-angle of the lateral accretion. Prof. François Guillocheau also explained about the behaviour of 3 types of rivers, (1) braided river, (2) low sinuosity river, and (3) high sinuosity river. In this case we have the high sinuosity river.

Day 4: 28 August 2021

By Panagiotis Giannenas and Esteban Gaitan

Objective of the day was to see a general panorama of the main successions from the Tremp Basin, focusing on how tectonic and climatic signals propagate from the source. Before departure PI Sébastien Castelltort presented two brief talks. First, a summary about tectonic and climatic signals, their origin (allogenic or autogenic), and their propagation along a source-to-sink-system. Later, a second talk was held about the key points of the tectonic and subsidence history from the Pyrenees.

Stop 1: Llimiana Panorama

During this stop the ESRs explained to the newcomers PIs a panorama discussed in the second day. This panorama shows the thrusting that exhumated the Cretaceous sequences, this uplift caused a tilting during the deposition of the Palaeocene sequences, explaining their lateral thickening within an overall E-W trending synclinal structure.

Stop 2: Llimiana Panorama – Alveolina Limestones

In the same location the ESRs described the facies of the Alveolina limestone, a lithology that spreads widely along the area. With assistance of the PIs it was done the interpretation of the sedimentary environment, concluding that it was carbonate ramp with storm influence under mesotrophic conditions. It was also discussed the global implications in CO2 changes and how these affect these types of environments.

Alveolina limestones

Stop 3: Claret Formation

During this stop was discussed the implications of the Claret conglomerate which is a member from the Claret Formation as the marker for the onset of the PETM. This interpretation is still debated. Part of the debate lies in the interpretation of isotopes like 18O and 13C, and a significant pre-PETM event marked by the isotopes. It was also discussed how the project using new proxies as the Hf-Nd in clays and XRD can provide further insights in this debate.

Stop 4: Erinya Panorama

In this stop the ESRs made a panorama drawing sequences from the Paleocene that lie unconformably over tilted Cretaceous sequences. Together with the PIs it was suggested an interpretation in which due to tectonics the Cretaceous sequences were tilted almost vertically, later on during a quiescence period the Paleocene sequences were deposited unconformably on top.

Finally, in the evening the PIs Emmanuelle Pucéat and Alex Whittaker gave two talks about their research. The PI Emmanuelle Pucéat introduced the Hf-Nd isotope proxy and gave two cases in which it has been used to track chemical weathering and denudation processes. The PI Alex Whittaker gave a case example of Pre-Cambrian rivers and how the application of paleo-hydraulics can provide insights about them.

Day 5: 29 August 2021

By Ewerton da Silva Guimarães and Ariel Henrique do Prado

Stop 1: Castissent Formation

We did our first stop above the Castissent Fm. There we could observe very well preserved outcrops of sandstone with coarse sand and some pebbles and cross bedding stratification. We also could observe preserved tridimensional dunes that allowed us to infer the paleoflow of this old river. After many discussions we concluded that this deposit has a high probability of having been formed by a braided river. After the discussion about the outcrop Prof. Francois Guilocheau gave an overview of the Source to Sink background since the 60's.

Stop 2: Castillo de Viacamp – Escanilla Formation

A profile located under the tower (Castillo de Viacamp) has been analyzed. The profile is composed of two different, distinguishable layers. The lower presents predominantly a reddish color with yellowish patches. The grain size is very fine (clay/ silt). The red color is the result of oxidative processes, whereas the yellow patches have been recognized as root fossils. More specifically, these are traces of biological processes driven by roots. Carbonatic nodules are also commonly found within this layer. The upper layer is composed of yellowish, grayish material. The overall grain size is larger if compared with the lower layer, up to very-fine, fine sand. Additionally, these grains are cemented by a considerable amount of carbonate, thus being classified as a calcarenite. No apparent bedding has been recognized. The fossil content is composed of a few gastropods and bioturbation traces.

This sequence has been interpreted as being part of a lacustrine environment. The roots fossils and oxidation process of the lower layer indicates a near-surface deposit, most likely a paleosoil. The carbonate nodules were possibly formed by the interaction of calcium-rich ground water with the soil. The upper layer, due to the content of carbonate and fossils have been interpreted as being a lacustrine deposit, even though lacking the tabular bedding. The sequence is recognized as the Escanilla Limestone, a member of the Escanilla Formation.

Castillo de Viacamp – Escanilla Formation

<u>Stop 3: Graus Conglomerates</u>

At the same stop an angular unconformity between the Escanilla Formation and the Graus conglomerate has been observed. This unconformity has been explained in terms of a dynamical equilibrium between erosion and uplift. A back thrust caused by the main thrust at the Mont Sec region uplifted the Escanilla sequences and, in order to compensate for that, an episode of incision was initiated. Thus, the Graus conglomerate incised into the Escanilla Formation, generating an erosive surface and the observed angular unconformity. After that Laure Guerit gave a presentation about how to properly measure grain sizes from a conglomerate outcrop.

<u>Stop 4: Benabarre Antenna Panorama</u>

We could observe from afar the deposits of the Graus conglomerates above the Cretacious layers in a clear unconformity. Meanwhile, we could also see these conglomerates deposited very close to the stop in Benabarre Antenna, on the other side of the valley. One hypothesis that could explain the discontinuity of this deposit is that the Graus conglomerates were deposited above all the valley in the past and after a drainage change of the region to the mediterranean the channels started and incisional processes on the valley and eroded a great part of the conglomerates. From this stop we could see deposits of the Tremp Formation and the Alveolina Limestones.

Day 6: 30 August 2021

By Marine Prieur and Pia-Rebecca Ebner

The objective was to have an overwiew of the Tremp Basin infill west of the Sierra de Sis. We therefore did a section along the Isabena valley from the northern edge of the syncline toward its axis and ended the day with a panorama of the area.

<u>Stop 1: Obarra, Vallcarga Formation (Santonian)</u>

The formation is mainly composed of grey marls with intercalations of centimetric to decametric sand beds: fine and very well sorted, sharp base with flute casts (north-west orientation after dip-correction), numerous current structures from hummocky crossed stratifications on the lower part of the beds to dunes and ripples on the upper part, some fining upward trends, intense bioturbations (Paleodychtions).

These elements indicate a mainly quiet deep-marine depositional environment. The sand layers correspond to a succession of high energy events that bring siliciclastics (turbidites). A cyclicity in the sandy events is observed. There are horizons with homogenic limestone clasts supported in a marly matrix, that contain diverse benthic foraminiferas and some corals. Therefore, the Vallcarga Formation is fed by two different sources: a siliciclastic system located in the South-East and local shelves that developed during the growth of north-south anticlines (e.g. Turbon).

<u>Stop 2: Fuentes de San Cristobal, Blue Marls to Aren Sandstones (Maastrichtian)</u>

Above the Vallcarga turbidites lays a thick unit of grey-blue marls that correspond to a lower offshore depositional environment. On top lay horizons of shaly limestones with quartz grains, benthic foraminiferas, bivalves, brachiopods, gasteropods and Thalassinoides burrows. These observations are indicative of an upper offshore depositional environment. The horizons above rapidly grade into very well sorted fine to medium sandstones with burrows, vegetation debris and clinoforms prograding towards the North. These are the Aren Sandstones, corresponding to a northward prograding delta. The whole trend shows a progradation pattern from deep marine to a wave-dominated delta.

Fuentes de San Cristobal

<u>Stop 3: Serraduy, Vallcebre Formation (Danian), Tremp Group (Thanetian), Alveolina Limestones (Lower Ypresian)</u>

On top of the Aren Sandstones lay Danian continental deposits (lots of paleosols) that are capped by the Vallcebre lacustrine limestone. Above is the Tremp Group, composed of continental red shales and two marine limestones with sandy to pebbly local occurrences. On top is a conglomeratic horizon made of amalgamated channels that correspond to the Claret Conglomerate. Compared to the Claret area, the Tremp Group is here thinner and the two marine incursions show a proximity with the shoreline.

An important shift in the paleocurrents is observed between the northward prograding Aren delta (Maastrichtian) and the South-West flowing Claret Conglomerate (Paleocene-Eocene boundary).

Stop 4: Roda de Isabena, N-S panorama of the Tremp Syncline

The panorama allows an insight on the westward prograding Roda delta that lays above the Alveolina sandstones. A major angular discontinuity is observed that corresponds to a paleovalley filled up with the Sis Conglomerates from Upper Eocene to Oligocene.

Roda de Isabena panorama

Day 7: 31 August 2021

By Aurora Machado Garcia and Philémon Juvany

The aim of Day 7 was to follow the Campo section in order to identify the sedimentary se-quences (Transgressive and Regressive) from the K-Pg boundary to the PETM and their associated paleoenvironmental transition from platform to coastal plain deposits. The section is located on the North-western flank of the Tremp-Graus basin. This is a broad E-W trending synclinorium located be-tween major south-directed thrust sheets, the Montsec to the South and the Boixols to the North.

Stop 1: the Campo section

This 300m thick succession is located on the abandoned road along the deep gorge of the Es-era river (South to the city town of Campo). We started by observing the prograding shallow marine Arèn sandstones at the base of the section. Just above this unit, Rudist fossils can be found implying a Maastrichian age. The K-Pg bound-ary occurs in deltaic plain deposits between the Rudist layer and Danian carbonates. The position of the K-Pg boundary is debated, some authors put it directly at the base of the Danian Limestone and some authors put it at the base of a black shale because of increasing pollen content within this inter-val.

The first sequence of the Danian shows massive fine-grained limestones, dolomitized, with thinning of the banks upward, less ooids toward the top and are interpreted as coastal plain car-bonates. Above, sub-aerial exposures mark the boundary with the second sequence of the Danian. This second sequence is characterized by Dolomites, Fine grained limestones and marls which are in-terpreted as sub-tidal to inter-tidal flat. The apogee of the Regression is recorded on the sabkha-like deposits showing brecciated porous dolomites, mottled red-beds, gypsum layers indicative of suprati-dal and continental conditions. The Danian succession is capped by a lacustrine Wackestone full of charophytes, ostracods and gastropods. The top of this limestone is made of Calcrete filled with microcodium and it is interpreted as the record of the 2.5My Selandian unconformity.

The Thanetian deposits overlying this horizon are mostly marine and record a period of marine transgression. The first depositional sequences Th-1 shows four successive intervals recording 3rd order cycle of relative sea-level change in a protected marine environment. Th-2 sequence is separated from Th-1 by an erosional surface and is generally more open marine than Th-1 due to a reinforcement of the marine transgression. A subaerial exposure cap the top of the Th-2 sequence, evidenced by the occurrence of microcodium.

The Ilerdian I sequence records the Paleocene-Eocene thermal maximum (PETM) and is divided in four distinctive intervals: Interval 1 corresponds to shallow marine environnement, Interval 2 shows fining-up channel-like bodies of cross-bedded and parallel-laminated conglomerates to coarse sandstones and would be the distal equivalent of the Claret Conglomerate. Interval 3 can be attributed to coastal plain deposits. Interval 4 is made of the Ilerdian Alveolina Limestone indicative of the maximum flooding stage of the sequence.

The Campo section

Stop 2: the Lacort Panorama of the Peña Montañesa

During the afternoon we went to Lacort to observe the Peña Montañesa from a distance and interpret the structure by sketching a panorama of the cliff. First it was observed that in certain por-tions of the cliff the bedding of the outcropping rocks (including the Alveolina Limestone) were appar-ently horizontal, but other portions it was not clear how the beds were dipping. In those uncertain parts it was possible to observe 'arc-shaped', or chevron, erosional features, indicating that the bed-ding was nearly vertical. By observing this difference in dipping angles we could conclude that the rock succession was folded and coupling that with the interpretation of the geological map, that gave us the approximate position of the Peña Montañesa thrust at the valley on the bottom of the cliff, we con-cluded that the structure is a fault-propagation fold. This means that the folding of the rocks occurred by a mechanism where the propagating thrust fault (the Peña Montañesa thrust) slips and terminates upsection by transferring its shortening to a fold developed at its tip instead of just rupturing the lay-ers. In this panorama view, we also observed the growth strata to the South of the deep marine suc-cessions of the Ainsa Basin.

To finish the day, we described a small outcrop where we could observe a well sorted, fine to medium grained, clean sandstone. In this sandstone, limited by an erosional surface at the bottom, we had hummocky cross-stratifications and the layer pinched out laterally. All this information combined allowed us to interpret the rock as being deposited in a wave dominated environment with influence of storms.

The Lacort Panorama of the Peña Montañesa

Day 8: 1 September 2021

By Aurora Machado Garcia and Marine Prieur

The day was split between fieldwork in the morning and presentations from some of the PIs in the afternoon. On the field we discussed about deciphering between autogenic and upstream or downstream allogenic forcings in continental records. The presentations were a great opportunity to know about the PIs work and to broaden our sight on S2S approaches.

Morning: Olson, Escanilla Formation (Bartonian - Priabonian)

The Escanilla Formation in Olson is composed of sandy to conglomeratic channels interbedded in floodplain deposits. From the church, the panorama shows an alternation between horizons with mostly isolated channels and horizons with a high rate of lateral amalgamation. The PhD of Nikhil Sharma focuses on trying to understand the cause of this pattern. Indeed, it could either be fully autogenic, or allogenic driven by upstream or downstream changes. He measured grain-size, flow depths and slopes to look for potential changes in paleohydraulics through time. Indeed, slope is a function of sediment and water supply (upstream forcing) and eustasy (downstream forcing). The question of a potential impact from the Mid-Eocene Climatic Optimum (MECO) is also raised and the sequences are compared to the Milankovitch cycles.

With a closer look at the outcrop, we discussed channels' architectures and the way to measure flow depths. Laure Guerit showed us the photogrammetry-based method she is developing to have an automated calculation of grain-size.

Dragonstone group in Olson

<u>Afternoon: Presentations from PIs</u>

Benjamin Gréselle started his presentation reiterating the importance of studying source to sink systems with a holistic approach. He commented on the importance of noticing the percentage of quartz and categorizing sediments using the QFL diagram to estimate reservoir quality. According to him, good reservoirs have high quartz percentage in their composition, so a source area consisting of volcanic rocks most likely will not produce a sink with good reservoirs, for example. He then shared a project from Neftex, where they aim to model the maximum depositional area of a source to sink system and the maximum deposition that area can accommodate. In their model, potential catchment, quartz content and reservoir quality are addressed.

Benjamin Bellwald focused his presentation on the importance and potential of using high-quality 3D seismic data when studying the subsurface. He explained how the acquisition of such high quality data is done and showed multiple examples comparing the usual seismic data to the high quality one used in VBPR, both in vertical and horizontal sections. He then proceeded to do an exercise, with the help of Amanda Wild, where a satellite image was showed with low resolution. He showed the same image repeatedly, each time increasing the resolution, highlighting the difference it can make in an interpretation to have higher quality data.

Miguel Garcés presented about magnetostratigraphy, which is essentially a grid for time. Magnetostratigraphy uses the reminiscent magnetization in minerals that records the polarity reversals of the Earth's magnetic field, allowing correlations and dating of the rocks. Miguel talked about the importance of combining litostratigraphy, biostratigraphy and chemostratigraphy to the magnetostratigraphy to have a better time constrain, especially because the latter only has two repetitive zones (isochronos). To end his presentation he showed an exercise of isochronos correlation. Fritz Schlunegger shared some of his work in the Molasse basin where continent–continent collision causes the construction of topography and the downwarping of the foreland plate. He provided a brief history of the subduction and fillling history at the Molasse basin, measured by cosmogenic nucleids in quartz. It starts with the upfill of the basin 30-25 Ma ago and the eastern part of the subduction being pulled down, creating a deep foreland basin. At 20 Ma, in the east, the slab is removed and the foreland basin becomes shallow marine. At the same time, in the central part, the plate is still being subducted. Finally, at 16 Ma, the entire basin is filled. He also explained how the subducted part of the tectonic plate is actually too light to be subducted that far, leading to a rebound that lasts from 5-10Ma ago.

Laure Guerit presented her work on distribution of sediment residence times, where she explained the delay for signals in the source, especially for coarse sediment. She went into detail on her model for topography of uplifted source, where there is no subsidence and steady state is reached, but only lasts for a short (fast) period. At the same time, we have highly variable rivers in the foreland basin. The models approaches phases of incision, deposition and remobilization of sediment. Individual grains can be tracked and one of the main conclusions is that bedload grains smaller than 1mm are transported much faster than the coarser ones, meaning that fine grained sediments reach the sink earlier. With that, she recommends measuring ions when studying sediment residence times instead of coarse clastic components, since they can be completely offset.

Pietro Sternai presented about modeling in 'deep Earth', focusing on average temperature variations in the Cenozoic that can be explained by the carbon cycle. He stated that tectonics, climate and surface processes have been always considered while the magmatic activity component was commonly overlooked. He explained how we can use loading and unloading on the surface to reconstruct the geothermal depth, how the relationship between climate and tephra frequency works and how the melting of ice and erosion of rocks create an isostatic rebound that culminates on magmatic activity. To exemplify, he showed a study case of his PhD student, Veleda Muller, where she analyses the volcanic activity in the Andes, modelling why we have volcanism happening in different places.

Day 9: 2 September 2021

By Iwan Setiawan and Lucas Valore

During this day we moved from Ainsa to Zumaia. Our objective is to see the deposits across the shelf and to the edge. We got to visit two locations along the way before the rain came. In the first location, we observed delta deposits of shallow marine (shelf) environment while in the second location, we observed carbonate platform located on the shelf edge.

<u>Stop 1: Yebra de Basa (Sabinanigo FM. equivalent to Escanilla Fm.)</u>

Our first stop is located several kilometers away to the west of Ainsa. We were at the anticline of Yebra de Basa resulted from the thrusts of the Pyreneean orogeny. In this location we observed he occurence of bioclastic contents (bivalves, gastropods, benthic forams) indicates that these sequences are deposited in shallow marine (shelf) environment.

At the bottom, it is dominated by marls deposits which correspond to prodelta environment. Then, it is overlain by alternation of calcareous sandstone (sandy limestone). We observed oxidized organic matter (pieces of woods, roots), burrows (bioturbations), mega ripples, and wave ripples in between which indicated that these are wave-dominated delta deposits. At the top, we observed tidal-dominated calcareous sandstone deposits which is inferred by ripples structures showing bidirectional flows. These structures are resulted from flow and ebb actions which bring sediments to the land and sea respectively. These are typical characteristics of tidal environments. The important things distinguishing these wave and tidal influenced in these deposits are the sorting differences, we observed more better sorting in the wave-influenced deposit and poorly sorted one in the tidal-influenced deposit. These deposits are part of Sabinanigo Fm. (equivalent to Escanilla Fm.) and are Bartonian (middle Miocene) in age.

Stop 2: Venta de Lizarraga (Lizarraga reef complex)

Moving farther to the west, we arrived at the top of the hill of Lizarraga reef complex. In this location, we discussed the Danian-Thanetian carbonate deposits. We were standing exactly on top of the distal part of prograding Danian carbonate platform. This carbonate platform consisted of corals and extended for about 15 km. The reef growth resulted in a big slope (almost a cliff). There are many karsts in this carbonate platform resulted from the Selandian base-level fall. It initiated the diagenetic processes due to mixing of sea and fresh water. This karstification could be used to measure the amount of base-level fall. During the Danian, it is dominated by progradation of carbonate platform (HST) and then it turned to retrogradation during Thanetian up until the Ilerdian Alveolina limestones.

Venta de Lizarraga panorama

Day 10: 3 September 2021

By Melanie Kling and Amanda Wild

The objective of the day was to understand the marine and most distal environment in the sink. An important point was separating and comprehending orbital drivers and changes within the source to sink system.

Stop 1: Mirador, Zumaia Beach

In the first location (at the beach near Mirador, Zumaia) we could see a lateral extensive alternation of white limestones and pink marlstones with varying thicknesses.We learned that each marl- and limestone package represents a precision, five packages a 100-ka-eccentricity and 20 packages a 400-ka-eccentricity cycle. The succession also contains green sandstone beds, which are turbidites. The Cretaceous–Paleogene transition is indicated by an iridium anomaly but could not be biostratigraphically dated so far because of a lack in biostratigraphic useful content. We discussed how the system could have been stressed by to the eruption of the Deccan Traps and the Chixulub impact. We also discussed how volcanic eruptions can amplify the carbon dioxide release by magma passing through organic-rich sediment and evaporites. At the transition, there is a drop in the siliciclastic content. The reason can be either a higher hemipelagic carbonate production or a decreasing clay flux. To better understand the processes, the changes in the hydrological cycle and shifts in the clay mineral composition can be the key.

Mirador, Zumaia

Stop 2: Playa de San Telmo, Zumaia Beach

The second location of the day was at the beach of the Playa de San Telmo in Zumaia where the GSSP of the Selandian and the Thanatian is. There were two sources for these marine deposits: 1) a carbonate platfrom for the limestones, and 2) a continent for the clays. The upper Danian deposits (red mudstones and thick limestones) are very condensed and unconformed further proximally. The Selandian deposits (grey marlstones and thin limestones) were deposited during a lowstand, which is the reason for the hiatus in proximal deposits. Due to the emerged carbonate platforms, there was a decrease in carbonate shedding and resulted in the thin limestone beds. There was also an aridification. The low precipitation was presumably the reason for the low amount of sand transport into the basin via turbidites. The Thanetian deposits (grey marlstones and thick limestones) were deposited during a high stand.

Playa de San Telmo, Zumaia

Stop 3: Playa de San Telmo, Zumaia PETM

The third stop was at outcrops a little further inland and above the restaurant access to the Playa de San Telmo beach. Here we discussed the PETM (56Ma), a global climate warming event (44 000 GT of CO2) that lasted only 200 Kyrs around the same time as a eustatic marine transgression event. Despite the PETM's short duration, the high magnitude of the event left a mass of rapid sedimentation (yellow-reddish in color) with little organization at Zumaia (and further inland as discussed during previous field excursion days). The PETM can be recognized geologically as an increase in siliciclastic flux with a negative 13C and mercury excursion as well as an increase in the stomata density of paleo-leaves. It was mentioned that, one should consider the ratio of organic material when interpreting the mercury excursion as organics can cannibalize the mercury.

Before discussing potential causes of the PETM, it was critical to consider the entire carbon cycle and potential feedbacks (a theme for the day). This involved discussing ongoing research and present understandings of carbon release, storage, and preservation within the geologic record. Many periods in time have experienced high volcanic activity, but not all of them produce a PETM event. Thus, many researchers believe that the atmosphere of the PETM was fueled through a release of carbon enriched magma (negative C13 excursion) through volcanism (mercury excursion) due to passing of magma through/heating up evaporites, charcoals, and gas hydrates overburden. Methane could have been introduced to the system due to the melting of methane clathrates in the ocean. However, based on the carbon 13 excursion during the PETM and the carbon 13 composition of different carbon sources, it is plausible that the PETM atmosphere was CO2 dominant, with some organic matter carbon released, and only a little from methane. ESRs should however keep in mind that this is an ever-evolving field of study. Again, the feedbacks of storage, release, and preservation are still not fully understood, but must be considered when reconstructing paleoenvironments and climate conditions.

Day 11: 4 September 2021
ESR retreat in Orio

Day 12: 5 September 2021
ESR retreat in San Sebastien and transfer to Ainsa

Day 13: 6 September 2021
By Ewerton da Silva Guimarães and Ariel Henrique do Prado

This was the first of a 4-day training under the supervision of Prof. Jean-Loup Rubino. This training consisted of a set of classroom lectures, and core and outcrop analysis in Ainsa. The first day of training was focused on the study of turbidite systems, Seabeams , 3D seismic and outcrop contributions to knowledge. The following topic were discussed:
- History of turbidity currents facie analysis.
- Triggering mechanisms at the origin of gravity deposits
- Definition of hyperpycnal flow.
- Submarine slope failures.
- Turbidites facies and classification.
- Bouma's sequence.
- Fan models.
- Canyons and tributary systems

Field Trip
<u>Stop 1: Mirador de Guaso</u>
The objective of this stop was to have a panorama of the South Pyrenean basin (Ainsa Basin) in the Ainsa vicinity. To the northeast, La Peña Montañesa could be observed, which is formed by Cenozoic Limestones. To the south, the Ainsa syncline is found. There, a general discussion about the evolution of the Pyrenees was carried out.

View of the La Peña Montañesa from Mirador de Guaso.

The Pyrenees has a strong Variscan inheritance and has been significantly influenced by hyper-extensional events during Cretaceous rifting. Despite the high magnitude extensional phases, there is no sea-floor to be found in the Pyrenean domain, evidencing that the mantle has not been reached by such events. It is estimated that, during the Paleocene, the Pyrenees experienced a period of tectonic quiescence, followed by the estimated beginning of its exhumation, around 45 Ma. Subsequently, a period of maximum shortening around Lutetian-Ypresian has taken place.

From the panorama spot, which sits on deposits of the Mid-Lutetian Guaso channel complex, a rough idea of the limits of the Ainsa basin could be sketched: The Ainsa basin, which is the Ainsa syncline, is bordered by the Boltaña anticline to the West, and by the Mediano anticline to the East. Upstream of the Mediano anticline is the Tremp-Graus basin to be found. Most of the sediments that filled the Ainsa basin have come from South and East. To the East, submarine lobes underlying the municipality of Boltaña can be found.

François Guillocheau, Jean-Loup Rubino, and ESRs

<u>Stop 2: Atiart Canyon</u>

The objective of this stop was to observe a geological unconformity due to a submarine canyon incision on the contact between the Castigaleu and Castisent formations, this unconformity is known as Atiart Canyon incision.

<u>Stop 3: Pocino Road</u>

The objective of this stop was to analyse the stratigraphy along the road and the maximum progradation of the Castissent Fm. into the marine environment. In this stop, in general, intercalations of relatively thick, fine-sand bed with mudstone/marl are present (Figure 3). The beds are laterally thinning and, despite the clear intercalations, no Bouma's sequence was found. The sequences have been interpreted as turbidites, which sometimes were found capping slump and debris flow deposits. The observations point to a continental slope environment. Furthermore, ichnofossils of zoophycos were found, supporting evidence of a continental shelf-brake environment. The debris flow deposits show episodic high energy transport of sediments that could indicate the progradation of the Castissent Fm. The combined presence of deposits of the Castissent Fm and of continental shelf points to a shallow water environment, but not yet a shoreface. The Pocino unconformity has also been observed in this region.

Intercalation of relatively thick, fine sand bed with mudstone/marly

Day 14: 7 September 2021

By Panagiotis Giannenas and Esteban Gaitan

The objective of the day is to learn the classification of turbiditic mechanisms, its architectural elements and identify them at outcrop. Please note that facies discussed in this report refer to Mutti's classification of turbiditic facies.

Morning lecture-seminar by Jean Loup Rubino on Turbidite systems: channel classification and architecture.

Course by Jean-Loup Rubino in Ainsa

Stop 1: Los Molinos section

The goal was to identify and understand facies of levee deposits, slumps, density flows and their relation to the nearby channels. Los Molinos section is an outcrop of approximately 100m thickness of marine sediments interpreted to be part of a turbiditic system ("The Fosado Turbidite Channel Complex"). From bottom to top, the succession records several cycles, but with an overall progradation trend. More specifically: levee deposits comprised of thin medium to fine sand beds interpreted as F9 facies (low density turbidity currents), with normal grading often having Ta to Tb and occasionally Tc preserved parts of the Bouma sequence. Levee deposits were often amalgamated with erosional bases and showed characteristic of slope environment ichnofacies. Beds appear to be thinning out away from the channels and overall thickening upwards to the top of the section. Two potentially individual slump events of 4-5 m thickness each were identified with a pronounced surface separating them. These were classified as slumps or as F1 facies indicating remobilization of sediments and perhaps an environment proximal to the slope or submarine canyon. Some minor sand injections were identified within slumps cutting through F1 facies. Top of sections: channels interpreted as F7 facies, medium to coarse grain size generally well sorted.

ESRs at Los Molinos

Stop 2: Ainsa channel in the quarry.

The goal of this stop was to identify the main channel structures and sequences. ESRs had to make their own interpretation in groups of four and present it to the PIs.

From bottom: clay dominated F9 facies debris flows or/and slumps underlying a larger scale erosional surface. Overlying facies consisted of erosional channels of F7 facies with some occasional shaly interbeds that appeared in an amalgamated manner indicating bypass. This section recorded overall upwards thinning of beds and upwards fining grain size as well as general lateral thinning.

Individual beds also recorded upwards fining grain size indicative of channels migration. Paleoflows directions were relatively scattered, but with a main domain suggesting a NNW flow. Other features observed were: top of beds with great amount and variety of trace fossils that indicated high biodiversity and bioturbation index. Base of beds with traces, groove and flute casts indicating paleoflow directions as well as oriented clasts and minerals.

Stop 3: Morillo de Tou locality, in the river:
The main objective of this stop was to observe F6 facies. This stop was important because we observed and identified F6 facies of one event within overall F9 facies of levee deposits in a distance of approximately 200m from the main channels. The main F6 feature is the presence of cross bedding related to a high energy event with medium to coarse grain size. F6 facies might be genetically related to a crevasse splay event. Finally, we observed the thinning and pinching out of the levee deposits of F9 facies (beds of multiple events) down-lapping onto a clay rich bed away from the channel as well as pairs of beds merging into a single bed before eventually pinching out.

Day 15: 8 September 2021
By Caroline Fenske and Rocio Jaimes-Gutiérrez

The main objective of the day was core description and analysis.

Morning lectures - With Jean-Loup Rubino and Fançois Guillocheau
- Lobes and sheet-like turbidites facies and classification
- Trace fossils
- Stratigraphic record

Afternoon: well log description
The core description exercise was done on the core “Well A3” which was bored in the vicinity of Ainsa. This project was developed by Kevin T. Pickering. These descriptions were performed, to recognize the different facies in the area; when comparing and complementing with the field data, we intended to get also the geometry. The wells and cores in the area were part of an international drilling project 20 years ago to understand the geology of reservoirs. This project also had the goal of being used as a teaching opportunity, offering the possibility of incorporating seismic, well logs, and direct observation at the outcrops. The well is approximately 230 meters from the Ainsa channel 1 and 2 outcrops (Ainsa Quarry). Other wells were bored in the region, all-around 100 to 200 meters away from each other. A detailed geological map was the result of these wells.

Core description workshop

The incorporation of core descriptions, seismic data, and field observations is essential. For example, we know from field observations that the paleoflow direction is N-W, with variations depending on the growth of the Boltaña Anticline. This cannot be seen in the cores, which are 1D representations of geological data. However, core description is important because it enables detailed analysis of facies, which is why combining both methods is of great importance.

Well A3 core description: the core has mainly debris flow material over sand. Shale facies were also dominant within the slumps. This is more abundant than in the Ainsa Quarry, which is interesting as the A3 well is not far away from the quarry. When looking at the whole system, the Ainsa channels visible in the quarry, are in the channels' axis, on the channels' beds. By contrast, the well is on a channel's margin, which is a lot more unstable and can collapse at any time. This explains the larger amount of debris flows. The shale facies can be explained through the growing mechanism of marine channels: coarse materials accumulate in the channel beds, but finer materials are suspended in water and can deposit on heights where coarse materials cannot deposit. A channel's margin is typically an environment where facies change very drastically and quickly.

Marine channel systems proved to be very interesting and different from continental systems. Understanding the processes in both systems can help to uncover their genesis. Their scale enables them to reach broad and distant areas, combined with fast transport of sediments. Every part of a channel/lobe system has its characteristics which, in the field, help determine in which part of the system the outcrop is situated e.g., grain size variations and bed thicknesses are determinant parameters to locate in a lobe or levee section. An essential part of paleoenvironmental analysis can be done through core descriptions, which give detailed information about the facies present. Combining both methods is the best way to understand and situate a system, as a 3D understanding provides a holistic approach.

Day 16: 9 September 2021

By Philémon Juvany and Pia-Rebecca Ebner

The objective of day 16 of the field trip had been the identification of lobe bed sequences, distinguishing their characteristic deposition from proximal to distal parts of the lobe system. The bedding character of the turbiditic systems, classified after Bouma (1962), is the primary indicator identifying lobe sections. The first stop of our trip led us Northward from Ainsa to Labuerda, analysing the Banastón Formation. Moving Westwards of Ainsa, the second stop had been in Buesa (Torla Formation) and the third in Yésero (Cotefablo Formation). Overall, our findings show that the structure and facies associations along the lobe sequences reflect distinct parts of the lobe and allow structural distinctions of the system. Furthermore, it may be assumed, that the lobe might represent an elongated structure, characterised by primarily parallel sediment beds along the system containing continental deposits.

Stop 1: Labuerda (Banastón)

The Banastón Formation, being related to the proximal part of the lobe complex, shows alternating layers of sandstone and shale, identified as F8 after Mutti (1992). It is predominantly made of Ta and Tb facies (classified after Bouma, 1962). The presence of less developed Tc facies, implied by slight ripple structures, and the absence of transported bed load leads to the assumption the formation being located at the margin of the lobe section. Compared to the Los Molinos section, reflecting highly developed ripple structures, indicating a high amount of Tc horizons, the Banastón formation shows no pinching out. Observed features are the characteristic upward coarsening and thickening, flutecasts and trace fossils (Thalassinoides). The presence of deposited erosional surfaces on top of the turbidite sections and amalgamated sandstone beds suggests that the location of sedimentation might be a channel lobe transition zone. Interbedded, reddish-coloured iron oxide-rich beds are observable, most likely caused by the long-stay of sediment after each sedimentation cycle in a hemipelagic environment.

Stop 2: Buesa (Torla)

The Torla Formation at the crossroads of the South entrance of Broto showed alternations of sandstone (F7) and thin beds of clay (F9). Compared to the previously identified proximal Banastón fan, more Tc horizons are present. The formation is still predominated by Ta and Tb, though showing a much greater quantity of sand, resulting in an approximate sand-clay-ratio of 3:2. Within the sand beds there are less, but still some pebbles contained. The coarsing up character of the sediment grain size distribution is less robust in this area, whereby even some parts show evidence of fining up. Clearly discernible is the lateral bed continuity of the facies sequence, being a key criterion in identifying the mid-lobe deposition.

Torla formation

Stop 3: Yésero (Cotefablo)

Representing the distal part of the lobe system, the Cotefablo formation is the time-equivalent of the Torre de Guaso Fm (Mid-Luteciann in age). Along the N-260 at the West of the Puerto de Cotefablo, the system shows a low proportion of Ta sections and highly developed Tb and Tc horizons. The latter indicated by clearly visible climbing ripple structures and convolutes. In comparison with the Torla formation, a greater amount of bed load can be found, reflecting a less turbulent sedimentation environment. An observable feature is an increased calcareous component within these facies, most likely induced by carbon platforms located southwards of the complex.

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