Ainsa Basin:

the archetype of a deep-water reservoir

Ainsa is a town located in the province of Huesca, Aragon in north-eastern Spain, close to France. It is geologically interesting because of its unique location just south of the Pyrenees mountains, with its exposure of outcrops analogous to subsurface hydrocarbon reservoirs in proximity to one another. The outcrops are exposed because of thrust faulting in the Pyrenees mountains during early Lutetian of the Middle Eocene. These outcrops include major plays of a conventional deep water hydrocarbon system from source to sink.

Field Day 1, April 23nd (Sunday)

Sunday morning was our first field day and we got up bright and early to head to Ainsa, our destination. On the way to Ainsa, we first got lunch then made our first field stops.

- **Overview of basin architecture of a deep-water system:** At Camarasa, we saw the southern border of the Pyrenees mountains, a series of Paleocene to late Eocene aged thrust faults as well as some beautiful poppies! The Pyrenees originated from the collision of the Iberian with the Eurasian plate and the uplift created a topographically depressed area—a basin around the mountain chain. Different regions of the basin separated by anticlines have been characterized and identified from south-east to north-west as the Tremp, Ainsa and Jaca basins. The Mediano anticline separates Tremp shelf fluvial deposits from Ainsa shallow marine/slope deposits while the Boltana anticline separates Ainsa shallow marine/slope deposits from Jaca submarine lobe deposits. Most of the material deposited in these basins was derived from erosion of the Pyrenees—delta deposits from the East and a conglomerate from the North.

- **Castissant sandstone up-close:** At our second stop, we looked at the Castissant sandstone, a fluvial deposit of the Tremp basin, which is well correlated to the deltaic sequences downdip. The Castissant sandstone is a coarse-grained sand interbedded with mud. These large point bar forms give us flow directions from shape and spread-out pattern of a deltaic lobe. This field stop was also filled with lots of wild lavender and thyme showing me the ways in which nature makes learning more enjoyable for geologists!

- **Mediano anticline**: Our final stop of the day was the Mediano anticline. The Mediano anticline is the geologic border of the Tremp basin and Ainsa basin. It separates the Tremp fluvial deposits from the Ainsa shallow marine deposits with a slope of about two to three degrees.

Field Day 2, April 24th (Monday)

Monday morning started out with a lecture at Apollo hotel on deep water systems. Apollo hotel was the ideal hotel for this field trip because of its proximity to most of the outcrops. It also came with a conference room/classroom equipped with a projector and screen for our morning lectures and onsite core lab.

Organizers:
Andre Droxler
Pankaj Khanna
Vitor Abreu
Keriann Pederson

With very little experience in deep water depositional systems, our morning lecture felt like a crash course. I appreciated Vitor Abreu taking the time to summarize what we had looked at the previous day before delving into the details of deep water systems. Vitor Abreu is an adjunct professor at Rice University with several years of experience in the Industry. He was our primary leader for the field trip and he also put together an excellent field guide for our use.

(from the perspective of a participant)

by Tami LongJohn

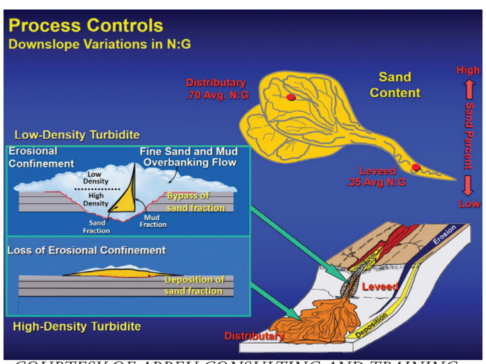
Photos by Gary Linkevich

April 22nd (Friday and Saturday)

It was a nice sunny afternoon when my co-travelers and I gathered together at the patio of the Keith Weiss Geological labs in Rice University to head to the George Bush Intercontinental airport. We were going away for a whole week to Spain to study ancient examples of deep water hydrocarbon reservoirs. In Spain, we would have the opportunity to see, touch and learn about deep water reservoir rocks that are typically found in the bottom of an ocean! After saying goodbye to loved ones, we set out on the Rice University shuttle to the airport. With an hour's ride to the airport, there was plenty of time to anticipate what this trip would be like. I personally wondered if the trip would be stress-free and utterly fun like a "geology-themed" vacation or if we would always come home from the field completely exhausted. When we got to the airport, we checked our bags, obtained our boarding passes and got some dinner. Soon after, it was time to board the plane to Turkey (where we would eventually connect to Spain) and we said goodbye to Houston. Perhaps my most cherished memory of the traveling was getting a row all to myself to spread out and enjoy a good night's rest! Two plane rides, three car rides, and more than 24 hours later, we arrived safely in Barcelona where we spent the night.

Between the 50s to 70s, a fan depositional model was proposed for fluvial (river) systems which gives a basic understanding of deep water depositional systems. From the fan model, proximal, medial and distal regions were identified and classified based on the distance from the shoreline. Although, this fan depositional model gives a basic understanding of deep-water depositional systems, some differences exist.

The differences between the fluvial and deep-water depositional systems was one important take-away from the morning lecture. In fluvial systems, flow is driven by the movement of water. So, I puzzled over how flow could occur in a deep-water system which is essentially a standing column of water. Was it possible for parts of a water body to be flowing while other parts were stagnant? My puzzle was answered by Vitor's explanation, that it was actually sediment flow driven by gravity. This flow of sediment, instead of water, is one way in which a fluvial system differs from a deep-water system. The sediment flow could lead to deposition if a reduction in flow velocity or slope occurred. Based on slope, three types of channels have been classified: (a) Strongly confined—about 1km long to 100m deep and typically more than 20 lithofacies (b) Weakly confined—about 1 km long to 1000 m deep (c) Distributive—1 km to 10 m and typically about four lithofacies. Additionally, three environments of deposition (EOD) were also identified as: (a) channel/channel fill (b) lobe/fan (c) levee.



COURTESY OF ABREU CONSULTING AND TRAINING

Another important take-away from the morning lecture was the short-comings of using the Bouma sequence to describe deep water lithofacies. The Bouma sequence is a naming scheme that was developed to describe and classify the different lithofacies in a fluvial system. Careful observation of deep water systems in recent years have revealed the occurrence of lithofacies that do not fit any category in the Bouma sequence. So, I learned that as a field geologist, observations of the lithofacies are more valuable than interpretations based on the Bouma sequence or any other naming scheme. Our interpretations can always change, but our observations do not!

- **Ainsa basin overview:** Our first stop was the top of a gorgeous hill with a bell tower. Here, we saw the entire Ainsa system which is composed of 4 major sandstone units –Gerbe-Banaston, Ainsa, Morillo, O'Grau. It was breath-taking view looking at the sand ridges as they got progressively larger with decreasing age. The icing on the cake for this stop was Pena Montanesa, a spectacular view of a snow-covered mountainous peak of the Pyrenees.

- **Gerbe-Banaston down-dip overview/up-close:** Our second stop of the day was an outcrop of the Gerbe-Banaston formation (GB), the first layer in the Ainsa System. We first studied a panorama of GB to get a general sense. The highlight here was a great example of bioturbation. Those little critters were surely happy enough to burrow their way through the sands! This was a clue to the energy level of GB.

An up-close study of GB allowed us to better appreciate the details. GB is a thick-bedded sandstone with terminations occurring within the bed. It has three types of lithofacies—a laminated sandstone, a cross-bedded sandstone and mudstone. We split up in groups and did our first measured section here to try to correlate the beds across the entire exposed outcrop of GB and better identify where the bed thickens or pinches out. Having never done a measured section before, this was a good learning experience for me.

The Great Lunch Debate

After our first two stops, we went to the park to enjoy a lunch buffet specially put together by our friends at Apollo hotel. This was the best lunch I have had in the field—(Croquetas, Tortilla, , Jamon (Ham) Serrano, Manchengo cheese) it was so yummy! Even more interesting than the lunch itself was the 'great lunch debate.' Our debate topic and one goal of this trip was to predict how the energy of the Ainsa system changed over time, and if accommodation (i.e. the space created by the depressed basin) was filled by depositional healing or progradation. Healing is associated with a decrease in slope, energy, confinement and fewer number of lithofacies with deposition, while progradation is associated with an increase in slope, energy, confinement and greater number of lithofacies. Vitor made us all pick a side, but the rocks eventually told us the answer.

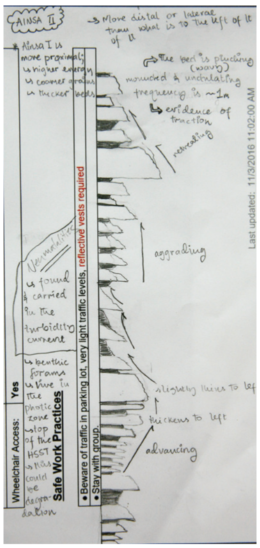
- **Ainsa 1 overview:** Our last stop for the day was the Ainsa 1 formation which, is the second formation of the Ainsa system. Most of the beds of Ainsa 1 are lens-shaped and terminate within the outcrop, and it is mostly a sand lithofacies. The interpreted environment of deposition is a lobe. The aggradational stacking of facies directly on top of each other could infer a channel avulsion (i.e. change in direction.) A comparison of GB to Ainsa 1 gave us a preliminary answer to the 'great lunch debate.' Since the number of lithofacies decreased between GB and Ainsa 1, it appears that accommodation is occurring by depositional healing!

We wrapped up the day learning about the similarities and differences in the flow profile (depth versus length) of a fluvial system and a deep water system.

Field Day 3, April 25th (Tuesday):

- **Ainsa 2 overview/up-close:** At our first stop, we got the big picture of Ainsa 2, then went to a quarry to study it up close and in more detail. Ainsa 2 has beds that are mounded and undulating with a frequency of approximately one meter. Compared to Ainsa 1 (which was seen the day before), Ainsa 2 is more distal, with lower energy, finer grains and thinner beds, indicating a less confined system. Vitor emphasized the importance of neatness and precision of our measured sections before placing us in teams to draw a measured section of Ainsa 2. The measured section gave us a better sense of the vertical stacking and range of thickness of the beds (my sketch from p.2 of guide book). Creating the measured section was the highlight of my day because it allowed me to see how much I had learned from the previous day's effort at the GB outcrop. I worked on a team with Nur Schuba (PhD student at Rice University and field trip participant), and we were very pleased with the outcome this time around! .

- **Morillo Rio Ara overview:** Our second and final stop of the day was the overview of Morillo from across the Sieste River. The Morillo group is composed of undulating sand beds with thinning towards the bottom-left and top-right. The muds in Morillo do not



show a lot of layering and are less continuous across the exposed outcrop surface, compared to the sands. Strong downlaps can be observed perpendicular to the flow direction. Based on the paleo flow direction (in the direction of Boltana anticline), we could see that the Morillo sands were laterally accreting (i.e. back-stepping during deposition). Before getting a chance to take a closer look at Morillo, we could feel drops of rain warning us that we were about to get rained on! We decided to head back to the hotel for the day.

After taking a short break, we sat down to an afternoon lecture delivered by Keriann Pederson. Keriann Pederson is an Industry professional with ExxonMobil and was our secondary leader during the field trip. Keriann was also on top of all the safety logistics during the field trip. We were introduced to two new depositional structures in deep water depositional systems namely antidunes and cyclic steps. Antidunes are symmetrical dunes that occur in deep-water systems. Just like in fluvial systems, dunes are also created in deep water systems. However, a difference exists in the style of deposition. Fluvial dunes are created by erosion on the lee side and deposition on the stoss side while deep water dunes, called antidunes because of their symmetrical shape, are created by the plastering of sediments on the same sediment package. Cyclic steps are sedimentary structures that result from hydraulic jumps i.e. a change in flow from super-critical to sub-critical. These flow types could be visualized using the example of a water fall. When flow is lateral and there is communication between the upstream and downstream parts of the flow, it is regarded as sub-critical. When flow is 'falling' and there is no longer any communication between the upstream and downstream parts of the flow, it is regarded as super-critical. These hydraulic jumps are one reason why we do not see big boulders in a fan because the big clasts fall out of a sub-critical flow. Flame structures and back steps (lateral accretion) can also be created when a hydraulic jump occurs.

Field Day 4, April 26th (Wednesday):

- **Morillo Rio Ara up-close:** Our first stop of today was the Morillo outcrop next to the hiking trail of a former monastery. Led by our fearless leader, Vitor, we hiked up the trail next to the Morillo formation, giving us the opportunity to touch and feel the outcrop. We identified three lithofacies in the Morillo—a silt-sized facies at the base, sand-sized facies with lots of organic matter and a conglomerate facies with large-sized clast—cobbles, gravels and boulders. The conglomerate facies is a good example of a debris flow. Debris flows are disruptive and erosive flows which can pick up large-sized clasts that float (i.e. no grain-on-grain contact) within the flow. Morillo was also filled with flute casts, scours and flame structures. These sedimentary structures are important because they are indicators of paleo-flow direction.

- **Morillo Sieste river up-close:** Further examination of the top of Morillo revealed a distinctly laminated silt-sized facies which is more folded at the top. There is also a debris flow at the top. The level of detail that we observed at this outcrop attests to the value of being able to walk up to an outcrop, observe and feel features that would be difficult to infer from a distance.

Afternoon Core Description

Our last activity today involved core description of the Ainsa system. This was by far the most exciting activity for me during the entire field trip. I was intrigued by the presence of a core lab in the basement of a hotel! Core labs are typically found in a specialized building on the campus of a university or an energy company such as Exxon. You certainly do not find them in hotels, let alone one in Spain. In fact, you will not find them in any other hotel in Spain except the Apollo hotel.

Vitor took the liberty to tell us the story of the birth of the core lab in the Apollo hotel. It all started out with the need for a place to store the cores that had been collected from different formations in the basin. Since Vitor was very good friends with Jose Antonio Florencio, the manager of Apollo hotel, he reached out to Jose and was given a spot in the basement. After years of running field trips out of the hotel, Jose noticed that the students were always on their hands and feet crawling around the floor during the

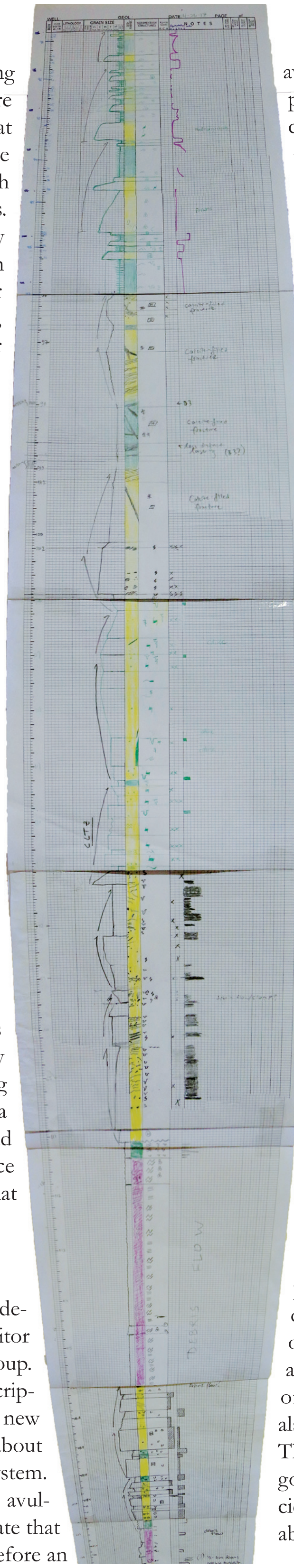
core descriptions. Jose suspected that something was out of place and asked Vitor how things were done in the industry. Vitor described to him that core description was typically performed in a core lab which was basically a well-lit room with high tables and storage under the tables for the cores. Within the span of a winter, Jose single-handedly built the core room based on the verbal description he had received from Vitor. When Vitor and other industry professionals found out about the room, they were beyond impressed and paid Jose a fee for building it! Since then, the unique presence of a core room at Apollo hotel has attracted different energy companies to run training courses at this deep-water reservoir system!

Before going to the core room, Vitor explained to us the basics of describing a core, which includes

characterizing the fabric, grainsize, bioturbation index, and sedimentary structures. In the core room, we got to work in teams again (I worked with Nur) to create a core description of Ainsa 1. This was an important experience for me because it not only exposed me to the process of effectively describing a core, but also taught me the value of working in a team. Nur and I made a great team because we could think critically about our observations and bounce ideas off each other when describing the features that we saw.

Field Day 5, April 27th (Thursday):

We started out the morning discussing the core description that we had created the previous day. Vitor first commented on the quality of our work as a group. He was very impressed and said that our core descriptions were even better than some he had seen from new industry hires! We also spent some time talking about the importance of bioturbation in a deep water system. Bioturbation can give an idea of the frequency of avulsion events. A high bioturbation index would indicate that a channel system had been stable for a long time before an avulsion occurred, and vice versa (photo of bioturbation index from my phone). Avulsions are also controlled by the size of a basin. A channel could cut into its own deposit if the basin is small or it could avulse to a different section if the basin is large.

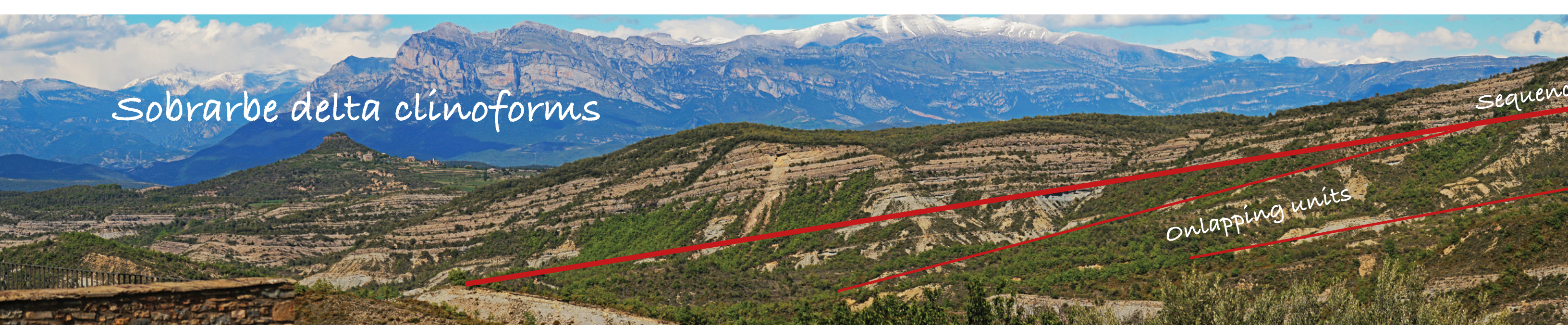


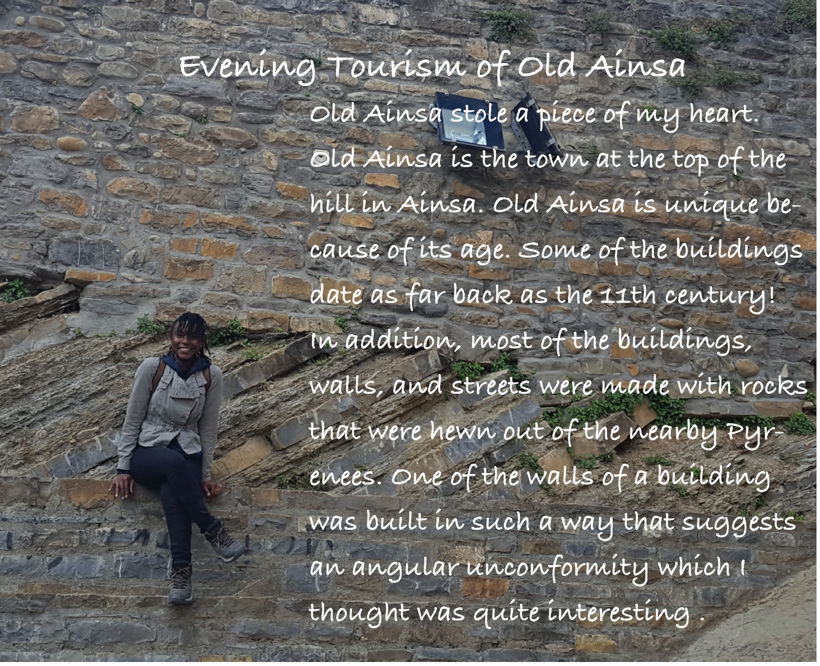
- **O'Grau overview:** Our first field stop was to get an overview of the O'Grau formation. We had to use binoculars at this stop. The lithofacies we observed were mostly sand with very little variation. Some bed sets extended across the entire length of the formation with a few pinching out within the formation.
- **O'Grau up-close:** After the overview field stop, we went to take a closer look at the O'Grau formation. This stop involved a one hour hike along a river which we had to cross in certain places. My male co-travelers had the opportunity to demonstrate their masculinity by tossing rocks across the river to create a bridge! It was a lot of fun to watch. The hike also provided the opportunity for me to chat with and get to know Renn Chang (Professional Science Master's Student at Rice University and field trip participant) from whom I learned a lot about Taiwan.

At the base of O'Grau, we saw that the sands were thickening and coarsening upwards; there was also a lateral grading of thinly bedded sections to more amalgamated sections. This gradation indicates that the highest energy depositional package was moving laterally. We interpreted the environment of deposition for this package as a lobe. At the middle of O'Grau formation, we were in a field of dunes!

Sobrarbe delta clinoforms: Our first field stop after lunch was an overview of the Sobrarbe delta clinoforms where a sequence boundary existed between O'Grau muds below, and carbonates mixed with siliciclastics above. A sequence boundary is simply an erosional unconformity. We mapped out the sequence boundary by identifying onlaps, a geometrical relationship between sediment layers, seen from the overview.

- **Carbonate platform:** Our field trip would not have been complete without looking at carbonates (see pano on previous page) because of our dearly beloved Andre Droxler. Andre Droxler is one of our professors at Rice University and the expert on carbonates. To say Andre was elated when we got to the carbonate platform would be a bit of an understatement! . One of the differences between siliciclastics and carbonates in the field is the pattern of weathering. Weathering of carbonates is characterized by circular holes. The carbonates were also filled with nummulites which are benthic/deep-water foraminifera. The presence of nummulites in a formation is often an indicator of a good hydrocarbon reservoir. The vertical stacking of the carbonate facies showed aggradation to progradation which we would typically find above a sequence boundary.





Evening Tourism of Old Ainsa

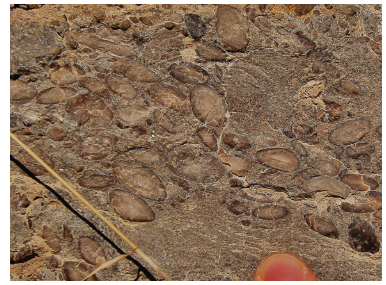
Old Ainsa stole a piece of my heart. Old Ainsa is the town at the top of the hill in Ainsa. Old Ainsa is unique because of its age. Some of the buildings date as far back as the 11th century! In addition, most of the buildings, walls, and streets were made with rocks that were hewn out of the nearby Pyrenees. One of the walls of a building was built in such a way that suggests an angular unconformity which I thought was quite interesting .

Field Day 6, April 28th (Friday):

Today was our last day in the field and we started out with a lecture summarizing what we had learned about the Ainsa system. During the lecture, we put together all our combined observations on the Ainsa system and discussed how the system had evolved in terms of energy based on the observations that we made in the field (sketch of entire Ainsa system from the guide book).

- **Jaca basin:** Our final field stop of the trip was the Jaca basin outcrop, which is a good example of hydraulic jump which is a change in flow from super-critical to sub-critical. We had previously discussed hydraulic jumps during the afternoon lecture of day three and it was great to be able to visualize it in the outcrops. We also observed mounding and thickening of the beds to the left; the thin-bedded sands to the right are a good candidate of a lobe avulsion. Furthermore, we observed a good example of the progression of beds in an idealized deep water system, from crude stratification to spaced laminations, ending with wavy beds. This is more representative of deep water systems than the Bouma sequence.

A good last question that was asked by Pankaj Khanna (PhD student at Rice University and field trip manager) was: "If we never knew that these were deep water outcrops based on geologic maps, and we came upon them for the first time, how would we know that they were deep water formations?" Vitor and Keriann explained that the two important indications were: (1) presence nummulite beds since nummulites are aquatic microbes, and (2) darker color of the muds since they would be less oxidized compared to surface formations.



Afternoon Road trip and Travel Home

After lunch, we said goodbye to Ainsa and headed back to Barcelona. As we drove out of Ainsa, I had mixed feelings. I was sad to be leaving because Ainsa had stolen a piece of my heart. At the same time, I was looking forward to being back home in Houston and being with my loved ones again. We spent the night in Barcelona, then headed to the airport very early the next morning. And that was it; we were Houston bound!

Almost a month after my unforgettable trip to Spain, I have had a chance to reflect on my experiences. I can say with all boldness that I learned more about deep water systems in a week than I have known in my last 7 years as a geology student. This field trip has trained my eyes to see and appreciate things in the world around me that the average person cannot. I can look at lifeless outcrops in the field and watch them come to life in my imagination because of this kind of field trip. The two most important things that I learned and believe I will keep with me throughout my career are: (1) Observations are more important than interpretations! It is better to have an accurate and complete record of the observations from an outcrop rather than the interpretation of what it could be telling us. Observations do not change but interpretations can! (2) Practice makes you better! My descriptions of outcrops and drawings of measured sections got better with each passing day. One thing that I think would enhance the learning experience even more is a daily introduction to some of the terminology used for this area of study. I found myself constantly asking questions about the meaning of terms to better appreciate their usage when describing the amazing geology that we saw.

Field trip organizers and participants (from left to right):
Front: Gary Linkevich, Tami LongJohn
2nd row: Renn Chang, Zuyue Zhang, Jennifer Holley, Calyn Jew, Minglong Pan, Harlan Zhang
3rd row: Chengzu Wang, Harsh Vora, Pankaj Khanna, Vitor Abreu, Skyler Wheeler, Yue Hou
4th row: Nur Schuba, Heath Hopson, Andre Droxler

Author Tami LongJohn and photographer Gary Linkevich

I am filled with so much gratitude towards Vitor Abreu and Keriann Pederson for taking the time to teach us about deep water systems and give us a deeper appreciation for the story that rocks can tell. I am also extremely grateful to Pankaj Khanna for all his hard work in making every single logistical detail run smoothly, and finally, Andre Droxler for all the support he provided behind the scenes. Also, Gary Linkevich (Thesis Master's Student at Rice University, fellow field trip participant and supplier of many of the images herein) was phenomenal in capturing all the precious moments during this trip which has made it easy for me to share my story. Finally, I must thank our friends at the Apollo hotel for their hospitality, and my co-travelers for helping me create these incredible memories.