

SALT THERMAL ANOMALIES
RESEARCH (STAR) CONSORTIUM

Research Proposal

**Thermal Impacts of Salt on Source Rocks and Reservoirs in the Paradox Basin, Utah, the
Western Pyrenees, Spain, the Lusitanian Basin, Portugal, and previously collected samples
from La Popa basin, Mexico**

Submitted To Industry by:

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Starting Date: Fall, 2012 Ending Date: Fall, 2014

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**SALT THERMAL ANOMALIES RESEARCH
(STAR) CONSORTIUM
(2012-2014)**

EXECUTIVE SUMMARY

Thermal Impacts of Salt on Source Rocks and Reservoirs in the Paradox Basin, Utah, the Western Pyrenees, Spain, the Lusitanian Basin, Portugal, and previously collected samples from La Popa basin, Mexico

A Research Proposal Submitted by Dr. Andrew D. Hanson
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Because salt is up to two to four times more thermally conductive than other sedimentary rocks the presence of salt within a basin has a major impact on heat flow within the basin. Outcrop studies, linked with subsurface data, of salt diapirs and welds provide the best datasets for examining the impacts of the high thermal conductivity of salt upon adjacent strata because of access (in contrast, wells adjacent to salt provide limited spatial access, and seismic does not resolve small scale features that can be seen at the outcrop). Understanding the thermal impact of salt is vital for understanding source rock maturity, calculations of hydrocarbon volumes, predicting diagenetic loss of reservoir quality at shallow depths and porosity preservation at unusually deep levels and is important with regards to hydrocarbon migration associated with salt structures. All of these issues impact salt-related play concepts and reservoir scale geologic models. The Paradox basin (UT, USA), the Basque-Cantabrian region (Western Pyrenees, Spain) and the onshore Lusitanian Basin, Portugal contain exceptional exposures of a variety of types of salt diapirs, salt welds, salt walls and mini-basins where the scale and geometry of features created by salt-sediment thermal interactions can be examined and sampled in plan view. Seismic data from the Pyrenees, along with planned acquisition of seismic data from the Paradox basin, together with our new outcrop data are shedding insights into the importance of heat flow associated with salt structures. The salt and salt-related structures in these basins provide high-quality, accessible exposures that are uncommon in the world, but which provide the only “ground truth” data that can be used to define and calibrate the presence, scale and importance of thermal impacts related to the salt.

This proposal seeks funding for the ongoing Salt Thermal Anomalies Research (STAR) Consortium. The consortium is a research effort that expands and explores important issues that other ongoing consortia studies have not addressed. An initial “proof of concept” project jointly funded by the Salt-Sediment Interaction Consortium (SSC) at New Mexico State University and ExxonMobil Exploration Corporation led to the establishment of our consortium in 2010 and this proposal seeks funding that will allow us to build on conclusions from the initial work, to focus research efforts on specific aspects of each objective listed later in this proposal and to test models and concepts that are spelled out in later sections of this proposal. The initial research revealed significant thermal anomalies associated with a subaerial diapir (see Fig. 1 for a schematic representation of the results) and continuing efforts have significantly expanded the types of features we have researched. This consortium works collaboratively with the SSC, which focuses on sediment response and structural issues in salt basins, but differs from it in that we focus on thermal issues, hydrocarbon migration and basin modeling related to salt. We also have excellent connections with the Basin and Petroleum System Modeling (BPSM) consortium at Stanford University.

The objectives of this consortium are to: 1) document the variability in thermal histories adjacent to different types of diapirs, welds, walls and mini-basins and determine the controls on that variation, 2) document the impact of varying thermal histories within single reservoirs adjacent to salt with regards to preservation/destruction of reservoir quality, 3) document the impact on thermal maturities associated with different structural levels of salt structures, 4) document the thermal variability associated with different types of salt bodies, 5) characterize the nature of fluid flow associated with salt features, and 6) link the results of outcrop studies to subsurface data and model the results with the intention of reducing uncertainty with regards to how hydrocarbon migration occurs next to salt structures.

The annual fee for subscription to the STAR Consortium is \$24,000 for a two-year period (2012-2014) for continuing companies and \$26,000 for new companies. Annual deliverables will be produced based on the total level of funding available and will include as many of the following as funding allows:

- (1) A yearly formal meeting, in which research results from the past year are presented. The venue for the next meeting will be in Moab, UT in October 2012.

The research meeting allows:

- (1) Participation of up to three of your company’s employees on a 1 day, post-annual meeting field trip to view salt related features of the Paradox Basin. The fieldtrip will showcase features related to the thermal impact of the salt on adjacent sediments. The field trip will

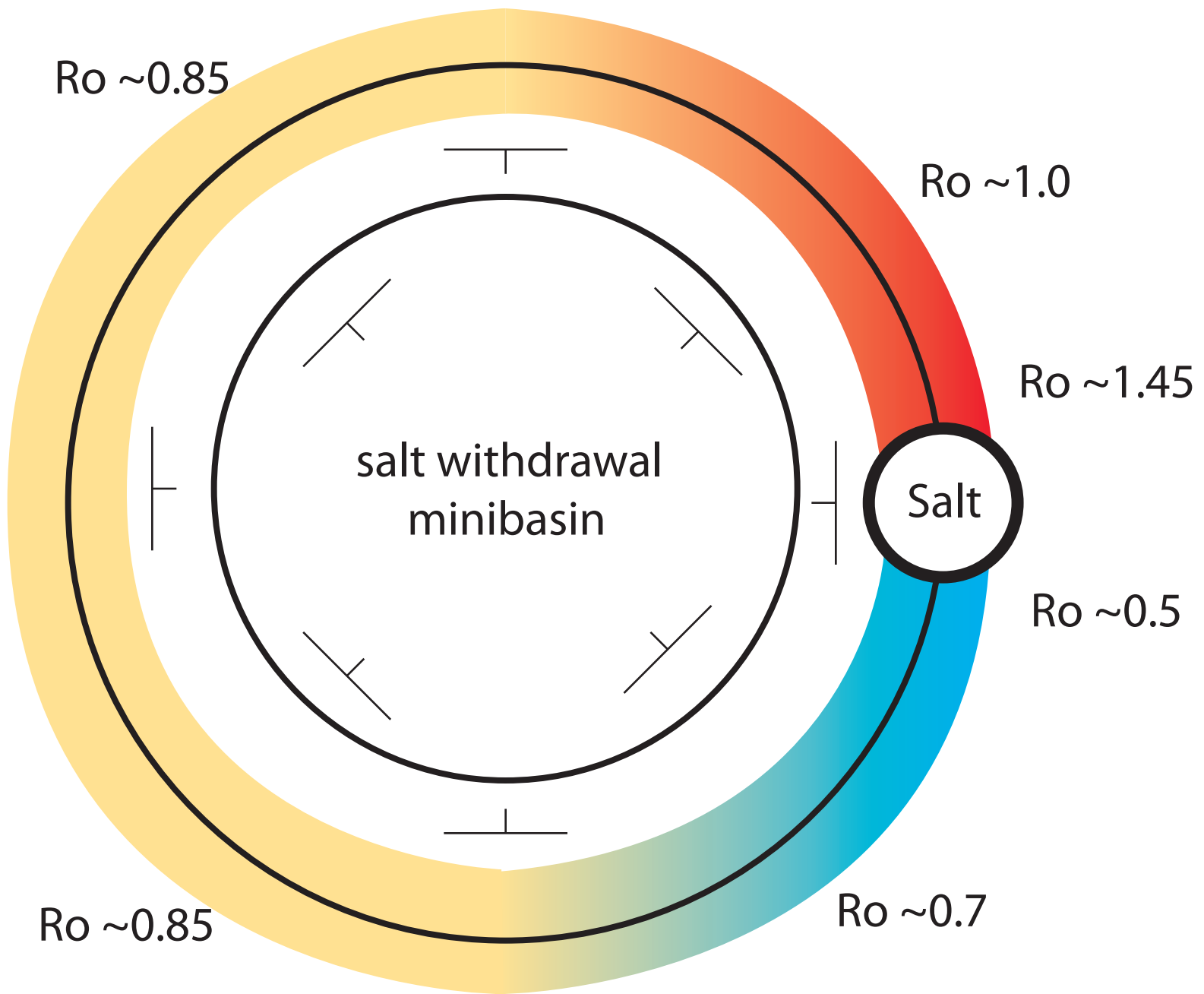


Figure 1 Schematic representation of variability in vitrinite reflectance seen in the "proof of concept" study completed by Hanson.

- (2) include a guidebook containing maps, cross sections, field and laboratory photographs, and other data sets compiled as part of this research.
- (3) Availability of digital research database upon request.
- (4) Preprints of all publications and theses.
- (5) Access to a password protected website, which has all research publications and guidebooks available to download.
- (6) An annual digital file containing all publications, abstracts, theses, and research completed during the year.
- (7) Qualification for private, custom designed fieldtrips for your company lead by the PI to either the Paradox basin or the western Pyrenees.

Funding for the consortium has generously been provided by ExxonMobil Exploration Company, Anadarko Petroleum Corporation, and ConocoPhillips.

In order to join the consortium, please contact Dr. Andrew Hanson (Andrew.hanson@unlv.edu) and we will provide a standardized agreement for your company to sign. Companies that initially elected not to join will be allowed to do so and will be given all previously generated knowledge and materials, but will pay a slightly higher rate their first year in the consortium. Should your company decide to leave the consortium it may do so by providing 30 days notice. In such an event no refunds of contributions will be provided.

RESEARCH PROPOSAL

Thermal Impacts of Salt on Source Rocks and Reservoirs in the Paradox Basin, Utah, the Western Pyrenees, Spain, onshore Lusitanian Basin, Portugal and previously collected samples from La Popa basin, Mexico

The Paradox Basin of eastern Utah, the Basque-Cantabrian Region of the western Pyrenees in Spain, and the onshore Lusitanian Basin, Portugal provide excellent outcrop analogues for salt features known primarily from seismic and well data of subsurface salt basins. Deposition of sediment in these basins is linked to salt movement and subsequent uplift and erosion has resulted in exposed salt diapirs, welds, salt walls and mini-basins. At these localities the scale and geometry of salt structures is beautifully exposed at the outcrop. Given that there are very few examples of these types of outcrop exposures anywhere on the globe, these features provide exceptional opportunities to understand how thermal conductivity and advection impacts maturation and reservoir preservation/destruction. By constraining how sediments adjacent to these structures are impacted by the salts thermal conductivity and advection we will be able to test, calibrate, and create new models of the thermal controls on sediments adjacent to salt structures. The resulting models and calibrations will provide important 3-D constraints for wells being actively drilled within salt basins around the globe. This proposal seeks continued industry funding for research to document the timing and scale of thermal impacts associated with diapiric rise and evacuation of evaporite masses in the Paradox Basin, the western Pyrenees in Spain and the Lusitanian Basin. Ongoing research on reservoir analogue samples previously collected from La Popa basin, northeastern, Mexico will also comprise part of the future research this consortium will conduct. No travel or work will be completed in Mexico: instead we will use samples collected in Mexico in 2008.

OBJECTIVES OF PHASE II

The proposed Phase II research will focus on 6 fundamental objectives. Each of the objectives is briefly summarized below and major conclusions drawn from previous studies are articulated. We then specifically address the new direction the proposed research will take as it pertains to that objective. We will collect new field data from appropriate areas in the Paradox and Pyrenees basins (and possibly from Cape Breton, Nova Scotia) and combine it with available subsurface data in order to test hypotheses and meet the following objectives:

Objective 1

Continue to document the variability in thermal histories adjacent to different types of diapirs, welds, and mini-basins and determine the controls on that variation.

Questions for Phase II:

- 1) To date we have documented both hot and cold anomalies associated with one of the diapirs we have worked on. At two other diapirs we see suppressed paleo-temperatures in near-diapir areas. Our preferred approach is to sample from a single stratigraphic layer that intersects the salt structure. This approach eliminates lateral variability in paleo-thermal maximum data (i.e., our vitrinite data) due to different burial histories. It also allows us to determine whether there is lateral variability in the strata we sample. We assume that uplift, erosion and subaerial exposure occur instantaneously (in geologic terms) so we rule out lateral variability related to weathering effects. Our overall goal is to determine how much, and what type of variability is produced by temperature regimes that existed adjacent to the salt (e.g., diapirs, walls) or salt related structures (e.g., welds).
- 2) The diapir we studied that has both hot and cold anomalies has always been assumed to be sub-vertical. Does the presence of hot and cold anomalies on opposite sides of the diapir suggest that the diapir is actually tilted and that the anomalies are linked to supra-salt and sub-salt positions? If so, are classic halokinetic sequences, which are well developed along one margin of a nearby diapir, actually sub-salt features instead of being features that develop off the sides of vertical diapirs? We have results from a second locality that exposes strata that previously sat in supra- and sub-salt positions and have recently collected additional samples from this locality to constrain the regional thermal story.
- 3) Does the size of a salt structure impact the scale of the thermal anomaly? Our first research was adjacent to a relatively small diapir but our research over the past year has expanded the scope of our project and increased the size of our dataset. Our goal is to document the variability of thermal anomalies and determine if these anomalies are scale-dependent. Do large welds have larger anomalies than a small diapir? Do salt walls have thermal anomalies that are of a different scale than those around diapirs? Modeling by Petersen and Lerche (1995) suggested that the temperature gradient associated with salt can vary out to about 1-1.5 times the salt radius, but our initial results and our new results from the past year contradict their predictions. Our newest samples were collected next to the largest diapirs that we've samples around thus far – will they have the biggest anomaly we have documented?
- 4) Can we capture current thermal variability around exposed salt bodies using remote sensing and surface data? Professor Nowicki (UNLV Geoscience) has expertise in using thermal imagery to address anomalies around salt, which we found helpful in our research on La Popa basin. One advantage of this methodology is that it can be used in places that are not very accessible (e.g., the Great Kivir in Iran). We have also started pilot studies using a hand held drill and HOBO Temperature probes that are installed for days/weeks in order to measure modern day temperature values of rocks adjacent to salt bodies.

Objective 2

Document and model the impact of elevated and depressed thermal maturities on preservation of reservoir quality and source rock maturation.

Questions for Phase II:

- 1) We want to continue to document and understand how vitrinite values vary around single diapirs and other structures. Our pilot study showed that temperatures at two points on opposite sides of the diapir were vastly different but we do not know how temperatures varied around the diapir.
- 2) Are elevated vitrinite values due to salt conductivity? Or are they controlled by migration of fluids derived from deeper in the basin? Or are they related to conductive cells that develop above salt? We have samples that can be examined to start to address these questions and we hope to analyze them in the coming year(s).
- 3) How have the different thermal histories we've documented adjacent to the studied diapirs impacted reservoir quality and source rock maturation? Quartz cementation is largely controlled by temperature so there should be a direct relationship between the thermal histories we are recording and the amount of cementation but this has not been constrained. We will point-count samples from sandstones in salt basins and analyze their chemistry in the UNLV SEM and Microprobe labs in order to determine cementation histories and see if these two phenomena are linked, as we suspect. If cementation varies within reservoirs adjacent to salt structures, how does that variability impact hydrocarbon migration into the reservoir? Our plans to constrain the cementation histories as well as our plans to model these systems should help shed new light on these issues. We are currently working on a suite of sandstones from the Permian White Rim Sandstone from the Paradox basin where obvious differences in the amount of quartz cement are linked to their distance from the Castle Valley weld.
- 4) Around diapirs with different paleo-temperatures, are pores in sandstones adjacent to the diapir more completely cemented on the side of the diapir where higher paleotemperatures were recorded? Conversely, are sandstones adjacent to the diapir less well cemented in the area where lower paleotemperatures were present? These issues have important implications for exploration teams that are targeting reservoirs near salt structures.
- 5) Is the scale of a thermal anomaly significant with regards to thermal maturation of a source rock in the basin? If so, how would these impact calculations of hydrocarbon volumetrics within a basin model? It seems intuitive that thermal conductivity in low permeability organic-rich shales (i.e., source rocks) will be vastly different than it is in adjacent porous/permeable reservoirs sandstones where advective heat transport is assumed to operate. By comparing how large the lateral thermal anomalies in the shales are (i.e., our vitrinite data) versus the lateral anomalies in the sandstones (i.e., our cementation/diagenesis data) we can start to model these units with reasonable temperature values.
- 6) Can we reduce uncertainties regarding hydrocarbon migration around salt structures by incorporating the thermal data into basin models? We will construct 2D and 3D basin models using Petromod that tie our surface data to available subsurface data (i.e., seismic, well data).

Objective 3

Document the impact on thermal maturities associated with different structural levels of salt structures.

Questions for Phase II:

- 1) Does structural level control the type of anomaly (i.e., are all shallow near-salt sediments anomalously hot whereas deep structural levels are anomalously cold) as modeled by Petersen and Lerche (1995)? If so this has important implications on reservoir preservation adjacent to salt bodies at great depths as well as on source rock maturation

- adjacent to salt. Modeling by Yu et al. (1992) suggested that at deep structural levels the difference in temperature between a point within the salt and a point within the adjacent sediments at the same depth could be as great as 50°C but no “ground truthing” has confirmed the validity of this work. We have a growing data set of vitrinite values from rocks that range in age from Miocene to Cretaceous that have experienced different depths of burial whose vitrinite values range from a low of 0.35 to as high as 1.86 %R_o. As our dataset continues to expand we should be able to answer these questions.
- 2) Modeling (Mello et al., 1995) suggests that temperatures in sediments that surround the top of a diapir will be elevated. Modeling and limited well data (Vizgirda et al., 1985) also suggest that sediments adjacent to the lower portions of diapirs will be colder because of the “wicking” of heat out of the sediments because of their proximity to the salt body. By testing anomalies in different basins that have been exposed at different levels we will be able to address these questions. As Petersen and Lerche (1995) pointed out this may mean that a potential source rock that is overmature in the adjacent basin may still be in the oil window adjacent to the salt structure.

Objective 4

Characterize the nature and timing of fluid flow at the salt sediment interface.

Questions for Phase II:

- 1) We (Hudson and Hanson, 2010) previously documented evidence of hydrocarbon migration adjacent to the weld in La Popa basin. We will map in the vicinity of the salt structures we target in order to document potential hydrocarbon migration sites and pathways, with specific focuses on locations displaying discoloration and remineralization as well as waxy-appearing soils that smell like hydrocarbons. TOC, Rock-Eval and conventional biomarker analyses will be utilized to determine the presence of migrated hydrocarbons. Is there evidence of hydrocarbon migration at our other study sites?
- 2) Is there a preferred fluid migration pathway and entrapment stratigraphy related to halokinetic sequence types? Our previous work (Hudson and Hanson, 2010) indicates that migrated hydrocarbons do not ubiquitously occur in all areas along the weld in La Popa basin, but rather are confined to certain localities. We hope to document additional migrated hydrocarbons adjacent to diapirs and refine our understanding of where migrated hydrocarbons occur. The results will be compared to the known halokinetic sequences (tabular versus tapered) and we will be able to address the relationship between fluid migration pathways and halokinetic sequence boundaries and facies.
- 3) Although we’ve found several places where temperatures were suppressed adjacent to salt bodies, we’ve hypothesized that there may be elevated temperatures in the sediments that are in very close proximity to the salt. We hypothesize these conditions because of the immediate proximity to the salt, as well as the presence of deformation (cleavage development, faulting) and presence of fluid flow. The Bakio diapir in the western Pyrenees provides an excellent locality to test these ideas and we collected and are currently processing samples (vitrinite and fluid inclusion data) from this site in order to test this idea.

Objective 5 (dependent upon sufficient financial support)

Determine the viability of using biomarker maturity parameters, apatite fission track analysis (AFTA) and (U-Th)/He thermochronology to assess thermal anomalies in Precambrian-Cambrian strata in the Flinders Range of Australia where different types of allochthonous salt

bodies (subhorizontal salt extrusions and salt canopies) crop out. The Flinders Range also has some of the best documented and exposed tabular and tapered halokinetic sequences exposed anywhere on Earth.

Questions for Phase II:

- 1) Can we use these techniques to document and quantify thermal anomalies adjacent to salt structures in pre-Silurian rocks? We assume we can, and by using these techniques we can expand our research on thermal anomalies to areas where the strata do not contain vitrinite (e.g., the late Precambrian-Cambrian Flinders Range of South Australia which contains significantly more types of salt structures than the other research areas).
- 2) We have used biomarker maturity parameters in the past and know we can effectively use them in pre-Silurian rocks, but the analyses are costly. Hanson was essentially co-advised by Professor Mike Moldowan at Stanford and continues to work closely with him in his biomarker lab. Can we secure adequate funding in order to use these methodologies? Hanson was classmates, and has worked collaboratively on other projects, with Professor Daniel Stockli who runs the premier (U-Th)/He lab in the world at the University of Texas at Austin.

Objective 6 (dependent upon sufficient data)

Begin modeling thermal maturity around specific salt bodies in the subsurface of the Gulf of Mexico (GOM).

Questions for Phase II:

- 1) Are sufficient data available in the public domain to be able to model thermal states around one of the diapirs in the GOM? If so, what data collected as part of this consortium impart the greatest influence on modeled results?

Geologic Setting of the Research Field Areas

Geologic Setting of the Paradox Basin, Utah and Colorado

The middle Pennsylvanian Paradox basin of eastern Utah and western Colorado developed southwest of the NW-trending Uncompahgre uplift (Fig. 2; Baker et al., 1933; Wengerd and Strickland, 1954; Elston et al., 1962). Thick cycles of Pennsylvanian shale, dolostone, halite and other salt minerals make up the Paradox Formation and define the limits of the basin (Peterson and Hite, 1969; Condon, 1997). Overlying the Paradox Formation are Pennsylvanian and Permian siliciclastic strata that fine upward and change facies to the southwest. These changes created complex facies and the resulting stratigraphic nomenclature is complex (Baars, 1961; Condon, 1997). Northwest-southeast oriented elongate salt walls that are the result of Pennsylvanian-Jurassic diapirism are characterized by thickening of strata into elongate minibasins between the salt walls (Shoemaker et al., 1958, Doelling, 1988; Trudgill et al., 2004).

The Pennsylvanian-Permian Cutler Group consists of arkosic alluvial deposits that are up to 5 km thick next to the Uncompahgre uplift. These proximal facies grade into a thick section of cyclic middle Pennsylvanian evaporite, shale and carbonate of the Paradox Formation, Honaker Trail Fm, and Lower Cutler Beds to the southwest (Barbeau, 2003). Marine, eolian, fluvial siliciclastic and minor carbonate members of the Cutler Group (Halgaito Fm, Cedar Mesa Fm, Organ Rock Fm, and White Rim Sandstone) in the southeastern and medial portion of the Paradox Basin interfinger with the alluvial deposits of the upper portion of the Cutler Fm deposited near the Uncompahgre uplift (Condon, 1997). Unconformably overlying the Cutler Group is the Lower Triassic Moenkopi Formation, which was also derived from the Uncompahgre uplift. The Moenkopi postdated important shortening-related flexural subsidence (Barbeau, 2003) but records continued diapirism in the salt anticline region in the NE part of the Paradox basin (Shoemaker et al., 1958; Shoemaker and Newman, 1959; Trudgill et al., 2004). Dolostone and gypsum clasts derived from salt walls that were exposed during the Early Triassic have been documented in the Moenkopi (Lawton and Buck, 2006).

Salt walls in the northeastern part of the basin trend NW-SE and extend from Oligocene intrusions in the La Sal Mountains to the southeast to a plunge termination at the Colorado River on the northwest. Gypsum, black shale and dolostone of the Paradox Formation crop out locally on the flanks and near the middle of the eroded salt wall and are well exposed adjacent to the Onion Creek diapir. Permian through Jurassic strata thin towards the salt walls and dip steeply away from the salt walls and are even overturned near salt walls. Unconformity bound halokinetic

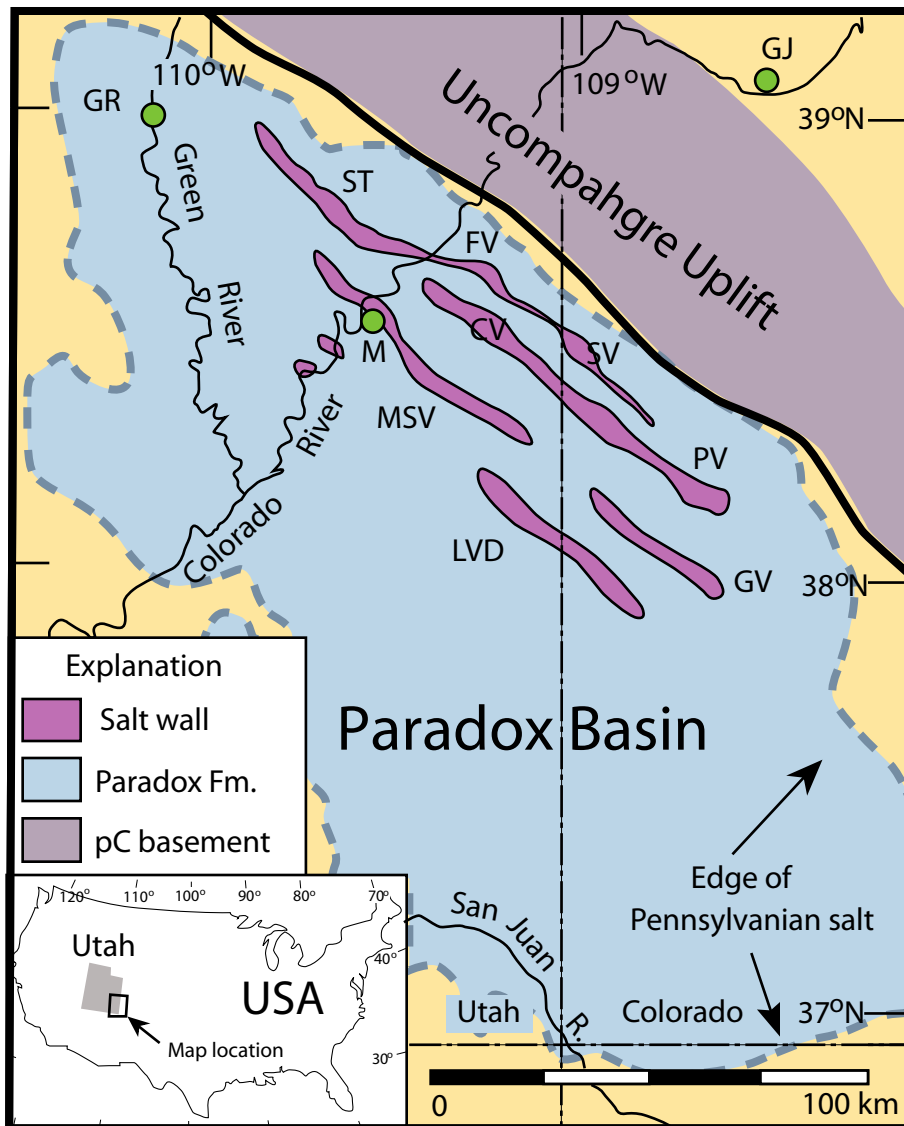


Figure 2 Map of salt walls in the Paradox Basin in Utah and Colorado, U.S.A. Towns include: GR = Green River, GJ = Grand Junction; and M = Moab. Salt walls include: ST=Salt Valley; FV = Fisher Valley; MSV = Moab-Spanish Valley; CV = Castle Valley; SV = Sinbad Valley; PV = Paradox Valley; LVD = Lisbon Valley-Dolores; GV = Gypsum Valley. Figure is from Lawton and Buck (2006).

sequences are defined by abrupt dip changes across bed boundaries in Cutler and Moenkopi beds. Lawton and Buck (2006) documented the Castle Valley weld in the Castle Valley area and strata appropriate for thermal anomaly studies crop out adjacent to the weld. We have initiated studies around the Onion Creek diapir in Fisher Valley (FV on Fig. 2) and next to a weld at the north end of Castle Valley (CV on Fig. 2).

Geologic Setting of the Basque-Cantabrian Region, Western Pyrenees, Spain

The opening of the North Atlantic margin resulted in deposition of Late Triassic evaporites in the area that would later become the western Pyrenees (Canérot et al., 2005). In the western Pyrenees alternative extension and shortening controlled the location and style of salt structures. Salt-cored anticlines initially formed above WNW-ESE trending basement faults (Fig. 3). Northeast-southwest oriented Aptian-Albian transtension subsequently caused salt domes to be exposed at the surface at the intersection of the earlier salt walls and the younger transtensional faults (Fig. 3). Some of these diapirs underwent dissolution post-Late Cretaceous and are filled with younger strata but as many as 20 different diapiric structures have been mapped in the region (Canérot et al., 2005). Geologic maps of the western Pyrenees (1:25,000 scale) available from Ente Vasco de la Energía revealed that lithologies adjacent to the diapirs are amenable to thermal anomaly studies and we have conducted field work adjacent to four of these structures. The abundance and distribution of diapirs in the region (some areas contain 6-7 diapirs separated by about 25km) make it ideal for understanding how anomalies are expressed in areas with a high density of diapirs. Because of the regional structure (less eroded and deformed to the south and west compared to deeper structural levels to the north and east) this area will also provide insights into how anomalies vary as a function of structural depth.

Geologic setting of La Popa basin

(site where sandstone samples collected in 2008, which we will analyze as reservoir analogues, were derived)

La Popa Basin, northeastern Mexico

La Popa basin lies within the Late Cretaceous to Paleogene Hidalgo/Laramide foreland system near the city of Monterrey in northeastern Mexico (Fig. 4). Mesozoic through Eocene strata in La Popa basin are deformed by northwest-southeast trending folds of the Coahuila marginal fold belt (Wall et al., 1961; Fig. 5).

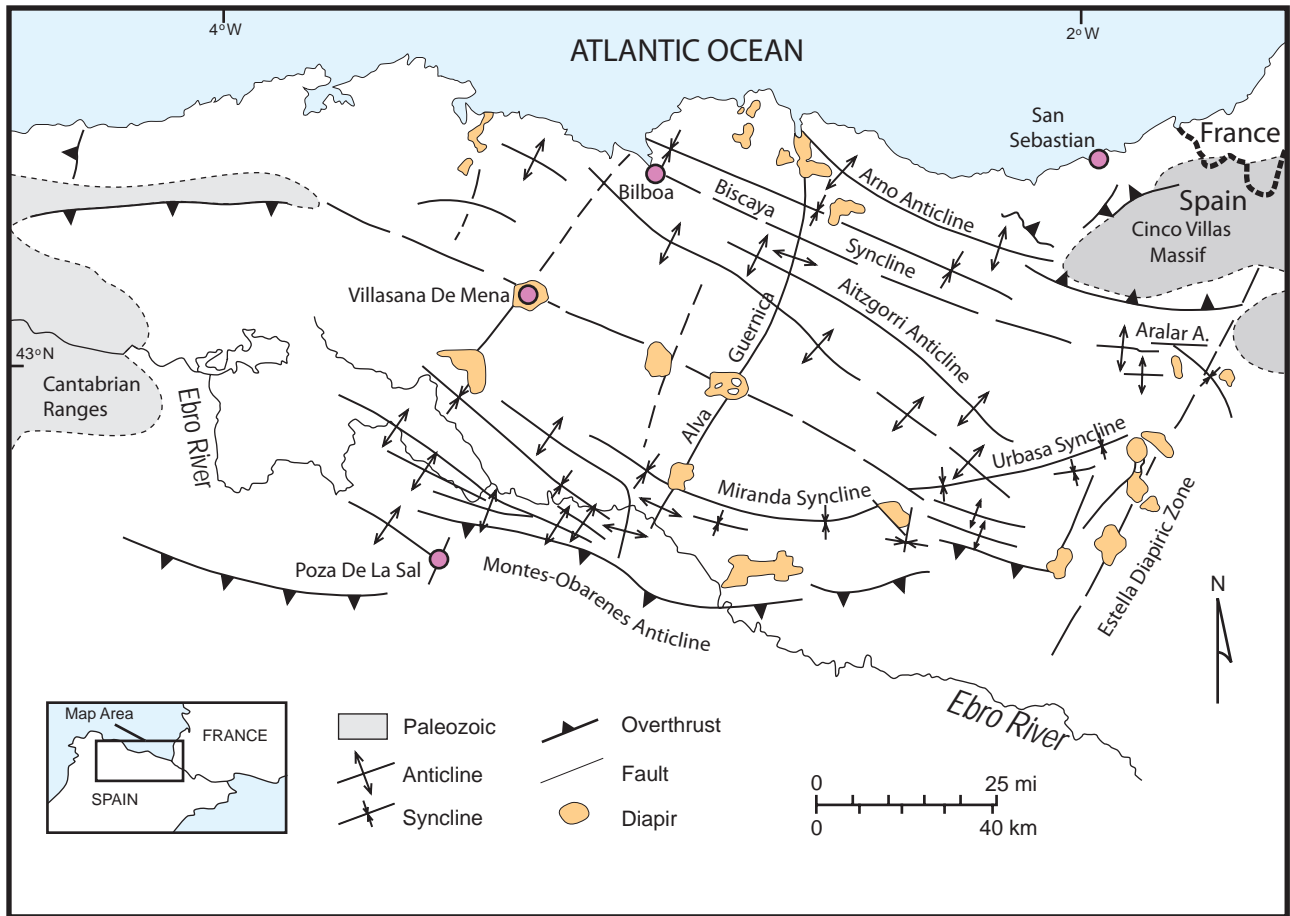


Fig. 3 Map of western Pyrenees showing location of multiple diapirs (from Canérot et al., 2005).

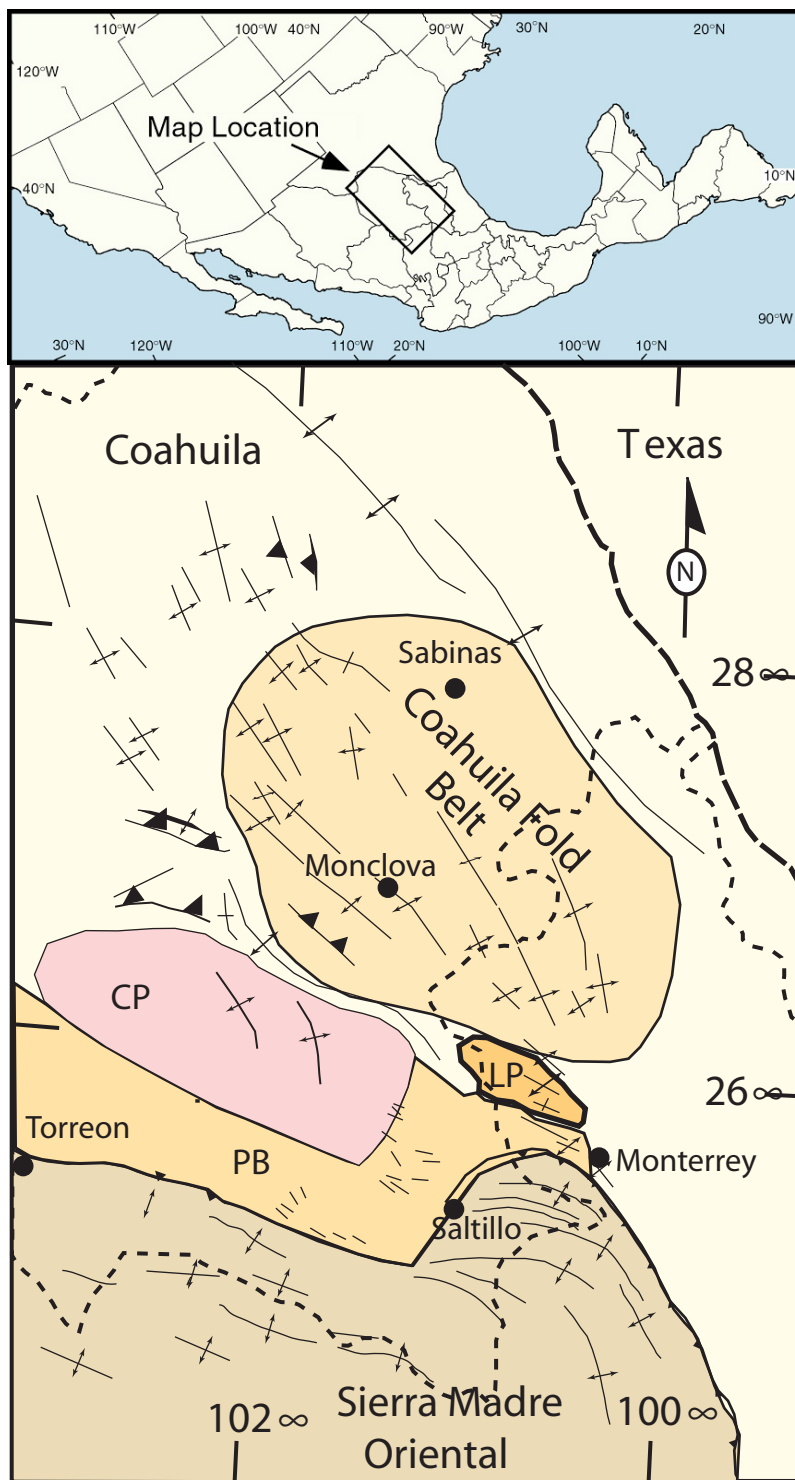


Figure 4 Box in the upper map show the location of the map in the lower box. The lower map shows the location of La Popa basin (labeled "LP") (taken from Giles and Lawton, 1999).

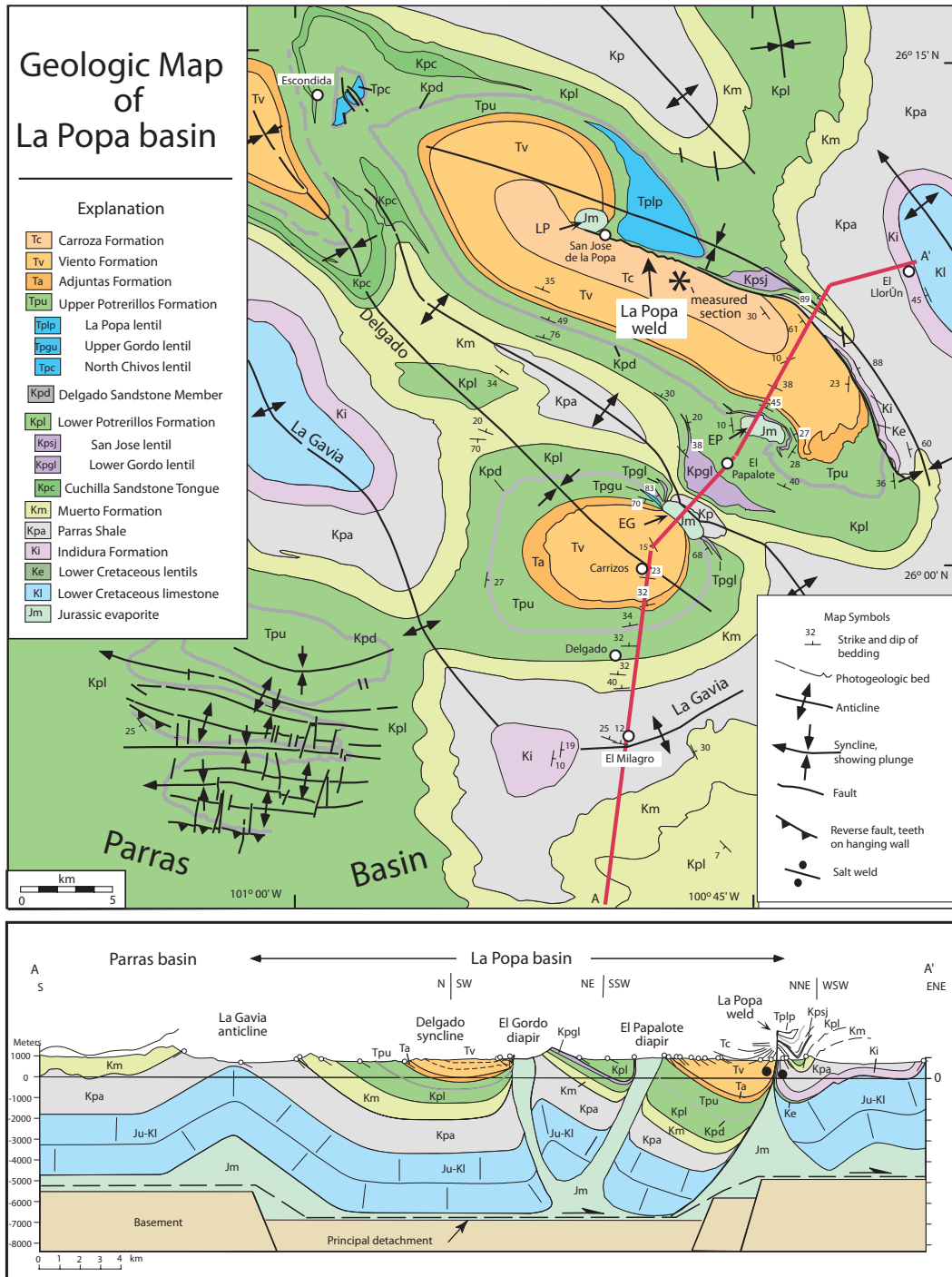


Figure 5. Geologic map and cross section of La Popa basin (taken from Giles and Lawton, 1999).

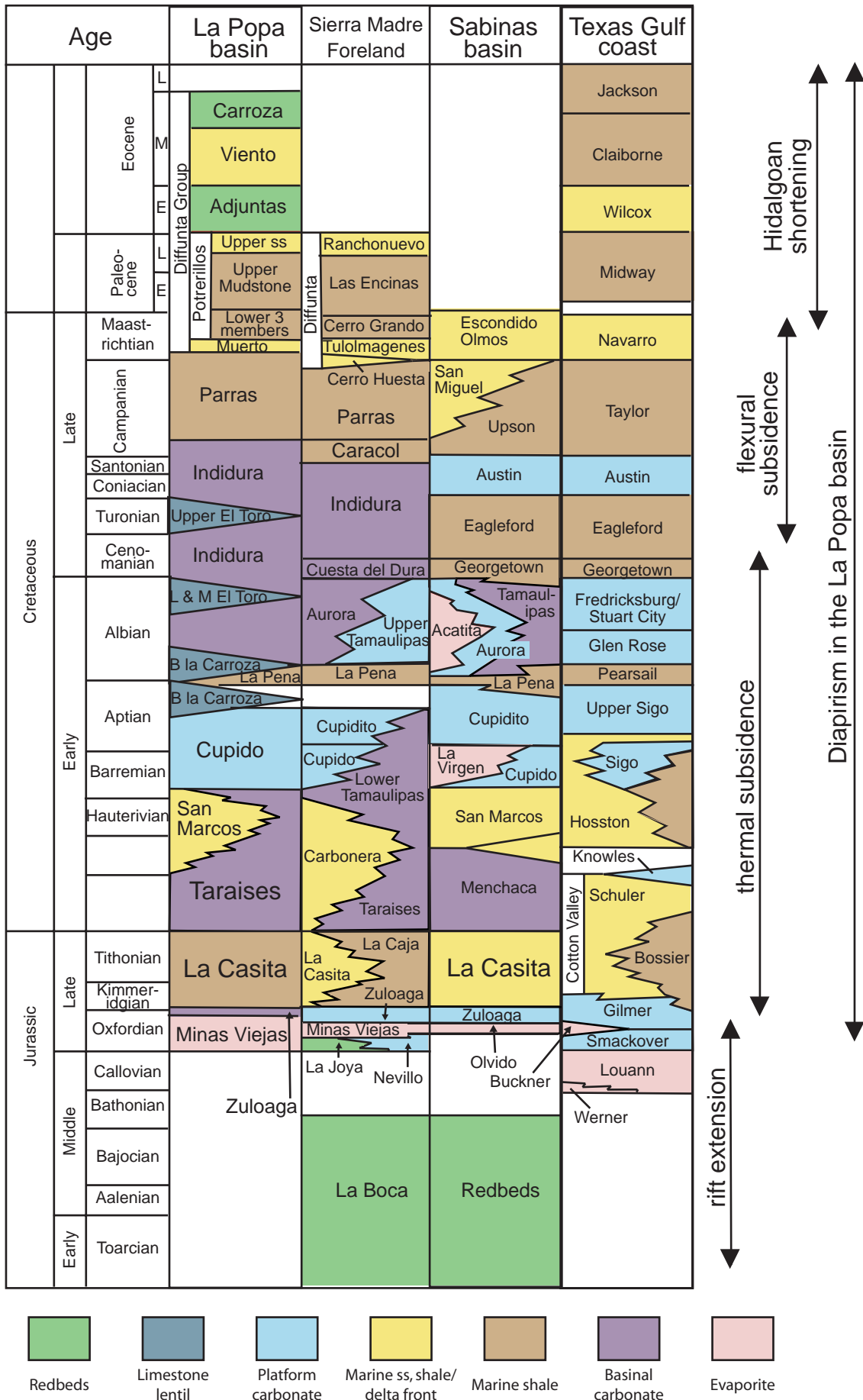


Figure 6. Stratigraphy of La Popa basin and adjacent areas (taken from Giles and Lawton, 1999).

La Popa basin contains an estimated 7.5km of Lower Cretaceous through Eocene strata (Fig. 6) (Hudson and Hanson, 2010). The bulk of the exposed strata consist of the Parras Shale and the Difunta Group, which range in age from Late Cretaceous (Campanian) to Eocene. The Parras Shale (Campanian) is less than 1200 m in La Popa basin and underlies the Difunta Group. In La Popa basin the Difunta Group is divided into five formations (Murray et al., 1962; McBride et al., 1974), in ascending order the Muerto, Potrerillos, Adjuntas, Viento, and Carroza formations (Fig. 6). McBride et al. (1975) and Ye (1997) showed that the units consist of primarily shallow-marine, fine-grained siliciclastic strata with subordinate marine to non-marine coarse-grained sandstone and conglomerate thought to be derived from a western source within the Sierra Madre Oriental. Locally present adjacent to evaporite diapirs are shallow marine carbonate lentils composed of oyster-rich calciclastic deposits and coral- and red algal-dominated reefs that rimmed the diapirs during near-surface diapiric rise (Hunnicut, 1997, 1998; Mercer and Giles, 2000; Druke and Giles, 2003, 2004). McBride et al. (1974) and Wolleben (1977) thought basin strata were almost entirely Cretaceous in age but new biostratigraphic studies (Vega-Vera et al., 1989; Vega and Perrilliat, 1989a, 1989b, 1992, 1995) in conjunction with work completed by the New Mexico State group indicate that the upper part of the Difunta Group in La Popa basin (Fig. 6) is Paleogene.

Three beautifully exposed salt stocks within La Popa basin (El Papalote, El Gordo, and La Popa) and a 25 km long, arcuate, vertical salt weld (La Popa weld) have been the focus of past research (Giles and Lawton, 1999, 2002; Rowan et al., 2003, Hudson and Hanson, 2010). The diapirs are roughly elliptical in plan view and have a surface area of 4-6km². The diapirs consist of a gypsum caprock containing entrained blocks of meta-igneous rocks and Jurassic carbonate (Laudon, 1984, 1996; Garrison and McMillan, 1997). The entrained blocks are thought to be derived from beds that were intercalated with the evaporite during deposition in an extensional Jurassic basin and carried along with the diapiric evaporite. Halite casts and a nearby well prove the existence of salt at depth. The diapiric evaporite was derived from Late Jurassic Minas Viejas and/or Olvido evaporite horizons. Diapiric evaporite exposures are surrounded by halokinetic growth strata of all ages exposed in the basin.

Geologic Setting of the Lusitanian basin, onshore Portugal

The Lusitanian basin resulted from rifting along the Iberian/Canadian margins that resulted in the opening of the Atlantic basin. Late Triassic precipitation of the Dagorda Formation resulted in extensive halokinesis throughout the rift stages that occurred throughout the Jurassic and into the

earliest Cretaceous (Alves et al., 2002). Different sections of the Lusitanian basin initiated and evolved somewhat independently of each other with the main Dagorda deposition occurring in the Central Lusitanian basin, an area near the central Portugal coast north of Lisbon and south of Navare (Fig. 7). Early Jurassic marine carbonates developed atop the evaporitic sequence (Alves et al., 2003). The carbonates transition into thick, mixed marine/nonmarine shales, siltstones, sandstones and conglomerates in the later half of the Jurassic when rifting initiated in the Tagus region to the southeast causing significant subsidence in the central Lusitanian basin. In some Lusitania sub-basins, a relatively varied Tertiary succession overlies the Mesozoic rift sequences. However, a widespread unconformity that caps a thin interval of earliest Cretaceous strata occurs throughout most of the central Lusitanian basin (Fig. 8). Our approach in the Lusitanian basin is to collect paired samples (mudstones for vitrinite reflectance and sandstones for diagenetic studies) along several transects that begin at the margins of the diapirs and extend several 10's of kilometers away from the diapirs. Numerous oil shows have been encountered in wells drilled in the Lusitanian basin and are presumed to have been derived from either Silurian black shales (Uphoff, 2005) or Mesozoic (Lias) source rocks within the basin. Subsidence modeling in the basin (Uphoff, 2005) suggests that our target strata should have experienced paleotemperatures that would put them within the oil-generation window.

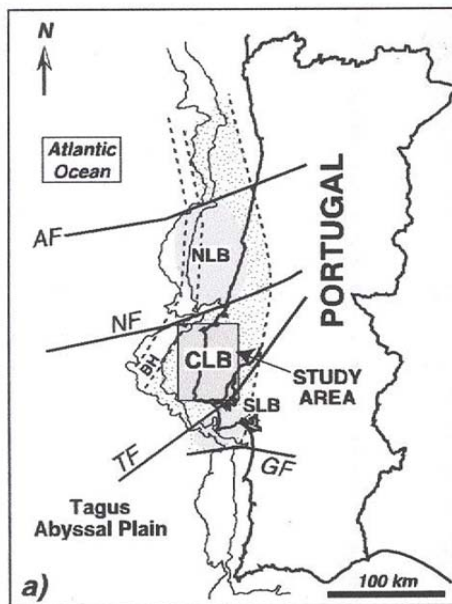


Fig. 7 Location map (from Alves et al., 2002) showing the location of the central Lusitanian Basin (CLB) between the Tagus Fault (TF) and the Navare Fault (NF).

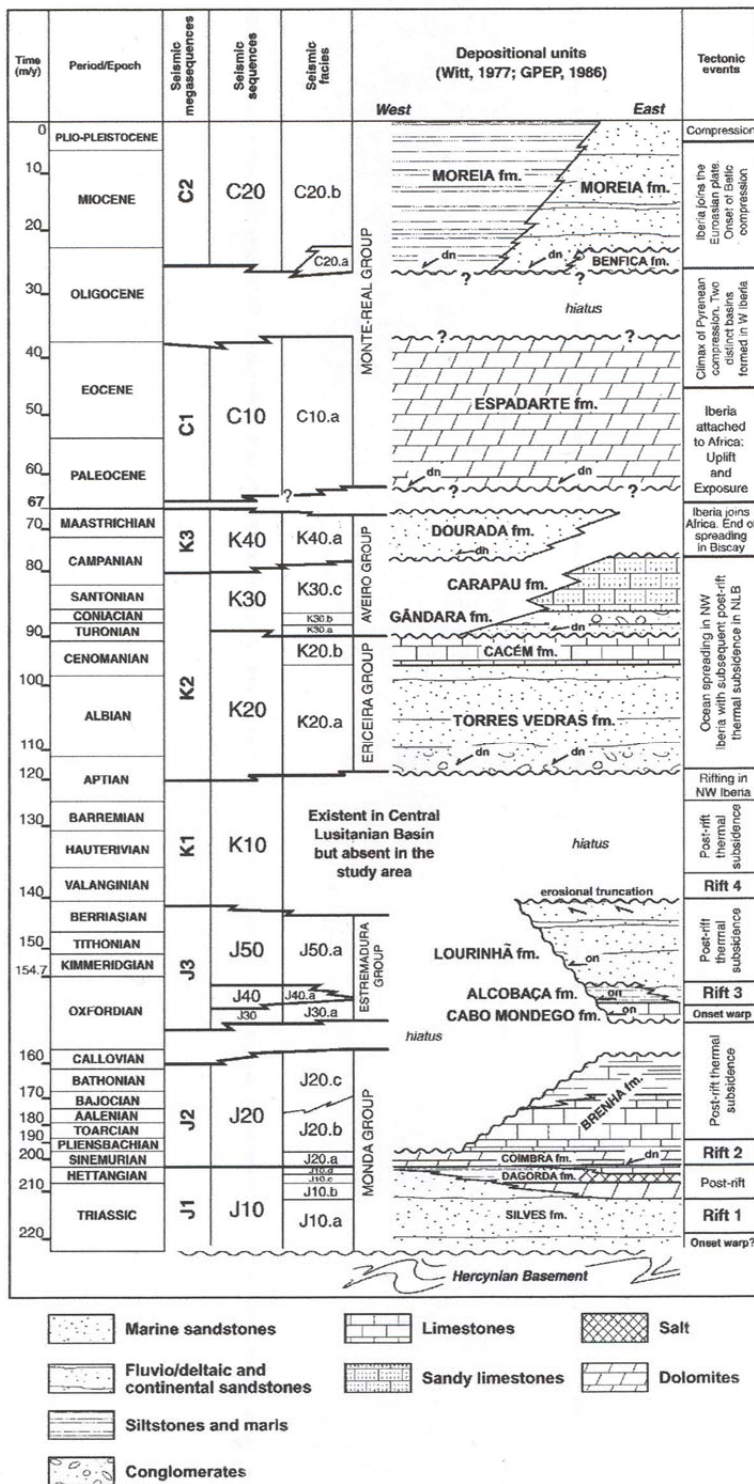


Fig. 8. Stratigraphy of the northern Lusitanian basin (from Alves et al., 2003). Diapirs are comprised of evaporites of the Dagorda Fm (L. Triassic) and targeted shales and sandstones are from the Jurassic Alcobaca and Lourinhã Fms.

SIGNIFICANCE OF THIS RESEARCH

Findings from this research has direct applicability to hydrocarbon exploration and production issues in basins impacted by salt tectonics. Thermal anomaly data derived from exposures in La Popa basin, Paradox basin, Lusitanian basin and the western Pyrenees will be of fundamental use in testing and calibrating existing salt-tectonic models derived from numerical models and well log studies and seismic of subsurface salt bodies. New models will be generated if existing ones are inadequate. Determining the patterns of near-diapir thermal histories will help in delineating the scale of maturity and reservoir preservation issues mentioned above. A better understanding of thermal anomalies will provide important predictive tools for determining reservoir extent and source rock maturity impacts in analogous fields. Regional documentation of thermal anomalies will ground truth previously published numerical models and thermal data of limited extent around salt diapirs. Documentation of hydrocarbon migration adjacent to salt diapirs will expand our understanding of how diapirism impacts hydrocarbon reservoirs and sealing capacities adjacent to diapirs thus reducing the risk associated with these important reservoirs. Importantly, accurate calculations of pay in discovery wells and prospects that are within near-salt temperature anomaly zones are dependent upon good temperature data because it impacts measured resistivity which is used to calculate water saturation (S_w). Lacking good data, company petrophysicists may miscalculate pay if their assumptions regarding thermal gradients near salt are incorrect.

The study areas provide exceptional field areas for schools aimed at teaching petroleum professionals the fundamental geometries of thermal anomalies around salt bodies and their impacts on migration and reservoirs which are normally only viewed on seismic and well log data sets. The basins are well- to very-well exposed and are easily accessible (the Paradox outcrops are a short drive from Moab, UT; the western Pyrenees are accessible by flying to Bilbao, Spain via Madrid, and the Lusitanian basin is less than an hour drive north of Lisbon, Portugal). The basins have different types of exhumed salt bodies and structures expressed at several structural and stratigraphic levels. The Paradox basin offers three dimensional exposures of halokinetic sequences developed on the flanks of large salt walls and a weld. Though not as accessible from the United States, nor as well exposed, the western Pyrenees in Spain, and the Lusitanian basin provide a wide variety of salt features and provide an important basis of comparison.

DELIVERABLES

Each of the primary objectives will be addressed by Hanson and Nowicki and their advisees. Graduate students will work on specific aspects of the stated objectives with Hanson organizing and coordinating the overall efforts. This will insure that the research stays focused and is completed in a timely manner.

We plan on having one consortium meeting per year, which will be held early each fall in either Moab, UT, Las Vegas, NV or Houston, TX. The meetings will generally have a day of oral and poster presentations that summarize the results of our research. The oral presentations include time to address individual questions or specific aspects of our research. Depending on location, the meeting may include a 1-2 day field trip to Paradox basin outcrops to view the salt structures and highlight the new research datasets completed during the previous year. If the meeting is held in Moab we will likely have the meeting in September or October. Over the 2 year duration of this project we may hold one of the annual review meetings in Bilbao, Spain and provide a 2-3 day field trip to the western Pyrenees. That meeting would be held in June or July for logistical and climatic reasons.

The primary deliverables will be preprints of all manuscripts, abstracts for meetings, student theses, and annual meeting presentations compiled each year as digital files and accessible for downloading from a password protected website. This will allow access to our results by subscribers prior to their publication. However, no restrictions will be placed by subscribers on our research in terms of content or timing of release to the general public once it has been presented to the consortium. An important deliverable is the annual meeting and field trip during which we will lead a 1-3 day field excursion (depending on the site of the meeting) to be attended by a maximum of 3 representatives from each participating company. The field trip will entail a tour of the primary salt bodies of the basin with emphasis on the recently completed research projects and outlining future work. The trip will include a guidebook. We also envision this as an opportunity for intellectual exchange between industry and academia in regards to understanding the nature of these very complex systems and helping the research team adjust the project focus to address issues faced by industry professionals. Participating companies will have access to our digital database upon request. Companies can also arrange, depending on time constraints and at extra cost, private field trips so that more employees can benefit from seeing these structures in the field.

COLLABORATIVE NATURE OF THIS CONSORTIUM

In the past Hanson worked closely with the Salt-Sediment Consortium at the University of Texas at El Paso (formerly at New Mexico State University). Their focus on sedimentology and structure fits well with our focus on thermal histories and diagenesis. All of their P.I.'s (Kate Giles, Tim Lawton, Mark Rowan) and Hanson have excellent, decade-long relationships. However, for logistical reasons imposed on us by our universities it makes more sense for us to have two separate consortia, but that does not mean that we work in isolation. We enjoy working together and want to work together as closely as possible. We are exploring ways in which our two consortia can collaborate more closely and are currently discussing ways in which we can work together in the field, which would allow us not only to have active on-going discussions on the outcrop as new insights are gained but it allows us to share field expenses and reduce redundancies in field and meeting planning. We are also discussing ways to hold joint annual meetings that would occur at the same location.

Hanson also has excellent relationships with the modeling group at Stanford where he was a PhD student under Professors Steve Graham and Mike Moldowan. Hanson also has a long standing relationship with Professor Ken Peters from the Stanford Group.

Having close ties with both the SSC and the Stanford Group allows us to leverage our results so that we can achieve greater results than if we worked alone.

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APPENDIX I

RESEARCH PERSONNEL

Principal Investigator: Dr. Andrew Hanson (University of Nevada Las Vegas) – source rock geochemistry, (U-Th)/He thermochronology, sedimentology, diagenesis, biomarker analysis, and fluid flow

The Principal Investigator is highly qualified for this project. Hanson's expertise is in basin analysis, sedimentology and petrology, thermal maturation, and biomarker studies of oils and source rocks. Hanson held an industry position prior to his employment at UNLV and has industry consulting experience. Hanson has extensive experience in the relationship of low-temperature geochemistry, sedimentology and tectonics. The following pages include a brief vitae for the Principal Investigator.

In addition, we will be supporting graduate students (both M.S. and Ph.D. students) and undergraduate majors from UNLV. The exact number will depend on the availability of qualified students and the level of funding that is received. I envision 2-4 graduate students and 2-4 undergraduate majors working on the project during the 2-year duration of the project. Hanson has successfully mentored 12 completed M.S. thesis projects, 2 completed Ph.D. projects, and is currently supervising 2 M.S. students and 1 Ph.D. student.

Dr. Scott Nowicki – remote sensing of planetary surfaces using thermal data
Faculty in Residence, UNLV Geoscience Department

Dr. Nowicki uses advanced remote sensing and GIS mapping techniques in combination with classical field methods to investigate the effects of natural processes on the properties and distribution of planetary surface materials. His primary research focuses on the thermal response of climatic surfaces on Earth and Mars. As part of our STAR team, Scott plans to use remotely sensed thermal data collected in areas adjacent to salt structures exposed in arid regions, and model the data to remove diurnal, seasonal, glacial-interglacial heat fluxes in order to assess modern-day thermal variability around salt structures.

Brett Perry
M.S. student, UNLV Geoscience Department

Brett Perry completed his undergraduate Geoscience degree at UNLV in May 2012. As an undergrad he was an outstanding student and was the top student in Hanson's undergraduate Sed/Strat class in the spring of 2011. Brett helped collect our suite of samples from the Paradox basin and continues to work on the cementation history of sandstone samples from the Paradox basin. Brett was accepted into the UNLV Graduate program and will work on samples from the Lusitanian basin where he and Hanson completed field work in the summer of 2012.

Tim Bright
B.S. student, UNLV Geoscience Department

Tim Bright is a senior in the Geoscience Department at UNLV. Tim is a non-traditional student who already possesses a B.S. degree in Journalism. Tim realized that his true calling is in geology and he hopes to pursue a career in petroleum geology. Tim is working with Hanson using a hand held drill and HOBO temperature probes in trial studies in order to determine their viability in documenting modern day temperature variability around salt bodies.

PAST PARTICIPANTS**Nick Downs**

MS Thesis, UNLV Geoscience Department

Nick Downs worked with Andrew Hanson's UNLV Salt Consortium and completed his MS degree in the spring of 2012. The son of a geophysicist, he grew up in Louisiana, Texas, and Doha, Qatar and completed his BS at Duke University in 2009. His master's thesis focused on the effects that salt diapirs have on the thermal maturity of surrounding sediments in the western Pyrenees, Spain. Nick is now employed by Chesapeake Energy in Oklahoma City.

ANDREW D. HANSON

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 Las Vegas, NV 89154-4010
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EDUCATION

1999 - Ph.D., Geological & Environmental Sciences, Stanford University
1993 - M.S., Geological Sciences, San Diego State University
1979 - B.S., Montana State University (6/79)

GEOLOGICAL EMPLOYMENT - *Post-Graduate only*

2006-present: Associate Professor, University of Nevada Las Vegas, Department of Geosciences
2000-2006: Assistant Professor, University of Nevada Las Vegas, Department of Geosciences
1998 - 2000 Exploration Geoscientist, Texaco International Exploration Division, Bellaire, TX.

RECENT HONORS

Associate Editor: Journal of Marine and Petroleum Geology, 2008-2012
 AAPG Foundation 2012 Professorial Award nominee
 UNLV 2011 College of Sciences Distinguished Teaching Award recipient
 Faculty supervisor of “2011 AAPG IBA Team, UNLV, 3rd place”, Rocky Mountain Section
 Invited nominee for 2009 ENI Award
 Elected UNLV Graduate Executive Council Chair for 2007-2008
 Sigma Gamma Epsilon, geology honorary society, faculty member, 2000
 Dean's Award for Extraordinary Service, Stanford University (1997)
 2nd Place Student Paper, 1997 AAPG Annual Meeting: Title: “Paleogeographic Implications of New Fossil Finds in the Altun Mountains, Xinjiang Province, NW China”
 Lieberman Scholar Nominee, Stanford University (1996, 1997)
 American Association of Petroleum Geologists Gordon I. Atwater Grant recipient (1996)
 ARCS (Achievement Recognition for College Scientists) Scholar, (1992)
 Phi Kappa Phi (elected 1992)
 Amoco Foundation, Inc. scholarship (1992); Chevron U.S.A. scholarship (1992); Roland and Caroline Eckis scholarship (1991); UNOCAL Corporation scholarship (1991)

PROFESSIONAL AFFILIATIONS

American Association of Petroleum Geologist, Active Member status
 Geological Society of America
 Society of Sedimentary Geology, Pacific Section of SEPM
 Nevada Petroleum Society

INVITED LECTURES (LAST 6 YEARS)

Molecular organic geochemistry of Railroad Valley oils and source rocks, Nevada Petroleum Society monthly meeting, Reno NV, Apr. 2012.
 A Surprising Thermal Anomaly around El Gordo diaper, La Popa basin, Mexico: Salt-Sediment Interaction Research Consortium Meeting, Moab, Oct. 2011.
 Basin Analysis of Synconvergent Basins in the Sevier Hinterland, and a Taste of Salt: USGS Anchorage, May 2011.
 Organic Geochemistry of Nevada's Known Oil Resources, and a Taste of Salt: USGS Denver, Apr. 2011.
 Thermal Anomalies Near Salt: UNLV Geoscience Seminar Series, Mar, 2011.
 Thermal Anomalies Near Salt: Basin and Petroleum Systems Modeling Industrial Affiliates

- Meeting, Stanford University, Stanford, CA, Nov, 2010.
- Basins, Biomarkers and Blistered Blobs: Australian School of Petroleum, Adelaide, Australia, Oct, 2010
- Organic Geochemical and Thermal Studies, La Popa Basin, Mexico: ConocoPhillips, Houston, TX, Feb, 2010
- PPP Presentation (on basin analysis): Geoscience Australia, Canberra, Australia, Jan. 2009.
- Impacts of Mobile Salt on Hydrocarbon Migration, La Popa Basin, Mexico, Nevada Petroleum Society, Reno, NV, Apr. 2008.
- Hydrocarbons along La Popa weld, NE Mexico: Basin analysis and basin modeling in a salt tectonics setting: GNS Science, Lower Hutt, New Zealand, Aug. 2007.
- Hydrocarbon source rocks in nonmarine basins: Insights from Chinese basins: International Conference on Non-marine Basin Systems: Depositional Processes and Products, Stratigraphy, and Petroleum Reservoir Exploration, Beijing, China, May 2007.
- Where Did That Quartzite Clast Come From: A Problem-Based Provenance Study: NSF sponsored workshop entitled "Teaching Sedimentary Geology in the 21st Century, University of Utah, July 2006.

FIVE MOST RELEVANT PUBLICATIONS

- Hudson, Samuel M***, and **Hanson, Andrew D.**, 2010, First documented hydrocarbons along a subaerial salt weld, La Popa basin, NE Mexico: American Association of Petroleum Geologists Bulletin, v. 94, p. 273-291.
- Andrew D. Hanson**, Bradley D. Ritts, David Zinniker, J. Michael Moldowan, and Ulderico Biffi, 2001, Upper Oligocene lacustrine source rocks and petroleum system of the northern Qaidam Basin, NW China, American Association of Petroleum Geologists Bulletin, v. 85, p. 601-619.
- A. D. Hanson**, S. C. Zhang, J. M. Moldowan, D. G. Liang, and B. M. Zhang, 2000, Molecular Organic Geochemistry of the Tarim Basin, NW China: American Association of Petroleum Geologists Bulletin, v. 85, p. 1109-1128.
- Zhang, S. C., **Hanson, A. D.**, Moldowan, J. M., Graham, S. A., Liang, D. G., Chang, E., and Fago, F., 2000, Paleozoic Oil-Source Rock Correlations in the Tarim Basin, NW China, Organic Geochemistry, v. 31, p. 273-286.
- Ritts, B. D., **Hanson, A. D.**, Moldowan, J. M., and Biffi, U., 1999, Early-Middle Jurassic source rocks and petroleum systems of the Qaidam Basin, NW China: American Association of Petroleum Geologists Bulletin, v. 83, p.1980-2005.

FIVE OTHER RECENT PUBLICATIONS

- Druschke, P.*, **Hanson, A.D.**, Wells, M.L., Gehrels, G.E., and Stöckli, D. 2011, Paleogeographic isolation of the Cretaceous to Eocene Sevier hinterland, east-central Nevada: Insights from U-Pb and (U-Th)/He detrital zircon ages of hinterland strata; GSA Bulletin, v. 123, p. 1141-1160.
- Ludington, Steve, John, D.A., Muntean, J.L., **Hanson, A.D.**, Castor, S.B., Henry, C.D., Wintzer, Niki, Cline, J.S., and Simon, A.C., 2009, Mineral-resource assessment of northern Nye County, Nevada; a progress report: U.S. Geological Survey Open-File Report 2009-1217, 13 p.
- Druschke P.***, **Hanson, A.D.**, and Wells, M.L., 2009, Structural, stratigraphic, and geochronologic evidence for extension predating Palaeogene volcanism in the Sevier hinterland, east-central Nevada, *in* Ernst, W.G. ed. International Geology Review Special Issue: Rise and Fall of the Nevadaplano – Part 1, v. 51, p. 743-775.
- Druschke, Peter A.***, Jiang, Ganqing, Anderson, Thomas B. and **Hanson, Andrew D.**, 2009, Stromatolites in the Late Ordovician Eureka Quartzite: implication for microbial growth and preservation in siliciclastic settings: Sedimentology, v. 56, p. 1275-1291.

Druschke, Peter*, **Hanson, Andrew D.**, Wells Michael L., Rasbury, Troy, Stockli, Daniel F., and Gehrels, George, 2009, Synconvergent surface-breaking normal faults of Late Cretaceous age within the Sevier hinterland, east-central Nevada; *Geology*, v. 37, p. 447-450.

*INDICATES HANSON GRADUATE STUDENT ADVISEE

Advisees of Hanson at UNLV:

1. **Brett Perry**, M.S. student; B.S., **UNLV**; Thermal maturation and temperature controlled diagenesis in the Lusitanian basin, Portugal, (in progress).
2. **Sarah Evans**, Ph.D student, B.S. **Univ. of North Carolina**, M.S. **Univ. of Kansas**, entering our PhD program in the fall of 2011; **recipient of the Jack and Fay Ross Family Fellowship** – awarded every other year to the best Ph.D. applicant to our department.
3. **Inessa Yurchenko**, M.S., student; B.S. **Moscow State University**, **ExxonMobil Scholarship Recipient**, Source rock assessment of several stratigraphic units in central Nevada, (in progress).
4. **Yuki Agulia**, M.S. student; **ExxonMobil Indonesian Scholar**; Determination of Maximum Late Paleozoic Burial and Timing of Permian Uplift in east central Nevada using Vitrinite Reflectance and U-TH/He, **Currently at ExxonMobil, Jakarta**.
5. **Nick Downs**, M.S. student; B.S., **Duke University**; Thermal anomalies around three salt structures in northern Spain, **currently at Chesapeake Energy, Oklahoma City, OK**.
6. **Carl Swenberg**, M.S. student; B.S. **UNLV**; Provenance and Geochronology of the Muddy Creek Formation, and Mapping in the Western Half of the Overton SE Quadrangle, Nevada, **currently at Chesapeake Energy, Oklahoma City, OK**.
7. **Laura Eaton**, M.S. student; B.S., **St. Thomas Univ.**; Linked Stratigraphic and Structural Analysis of the Frenchman Mountain Fault, Southern Nevada, **currently in the Ph.D. program at the University of Minnesota**.
8. **Tom Muntean**, 2011, B.S., **UC Santa Barbara**, M.S., **Univ. of Nevada Reno**; Ph.D. dissertation; Muddy Creek Formation: A record of late Neogene tectonics and sedimentation in southern Nevada; **Currently an Assistant Professor at Adrian College, MI**.
9. **LaOde Ahdyar**, 2011, M.S. thesis; **ExxonMobil Indonesian Scholar**; Oil-Oil and Oil-Source Rock Correlation Study, Railroad Valley, Nevada; Currently at ExxonMobil Indonesia, Jakarta; **Currently at ExxonMobil, Jakarta**.
10. **Steven Forrester**, M.S. student, 2009, B.S., **Washington State Univ.**; Provenance of the Muddy Creek Formation Near Mesquite, Nevada; **Currently at Providence Engineering, Baton Rouge, LA**.
11. **Peter A. Druschke**, 2009, Ph.D. dissertation, The Sheep Pass Formation: A Record of Late Cretaceous and Paleogene Extension Within the Sevier Hinterland, East-Central Nevada; 2003, MS thesis, The Age, Stratigraphy and Tectonic Provenance of Clastic Deposits in the Western

Bikou Terrane, Southwestern Qinling Mountains, China; B.S. **Sonoma State Univ.**; **Currently at ExxonMobil Exploration Company.**

12. **Nathan R. Suurmeyer**, 2008, MS thesis; Basin Analysis of the Central Grand Wash Trough, NW Arizona: New Insights into a Miocene Extensional Basin; B.S. Gustavus Adolphus Univ.; **Currently at Shell, Houston, TX.**

13. **Kati Gibler**, 2007, MS thesis, Postcollapse Volcanism in the Valles Caldera, New Mexico: The Transition from Large Volume Explosive to Small Volume Effusive Eruptions; B.S. Univ. of Alaska Anchorage; **Currently Owner of Gibler Geotechnical Consulting, Las Vegas, NV.**

14. **Jonathan G. Zybala**, 2004, MS thesis, B.S., **Univ. of Buffalo**; Stratigraphic Evolution of Las Vegas Bay, Lake Mead, Nevada: 1935-2002. **Currently at ExxonMobil Production Company, Melbourne, AU.**

15. **Samuel M. Hudson**, 2004, MS thesis, B.S. and Ph.D. **Univ. of Utah**; Hydrocarbon Occurrences Within the La Popa Basin: Potential Source Rocks, Thermal Maturation, and Hydrocarbon Migration along the La Popa Salt Weld, La Popa Basin, NE Mexico; **Currently at ConocoPhillips, Houston, TX.**

16. **Michelle M. Williams**, 2003, MS thesis, B.S. **Notre Dame Univ.**; Depositional History of the Black Mountain Conglomerate, Mohave County, Arizona: Sedimentary Responses to Tertiary Extension; **Currently at ENI, Houston, TX.**