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Research Proposal

Salt-Sediment Interaction Research Consortium

Submitted by:
Katherine A. Giles
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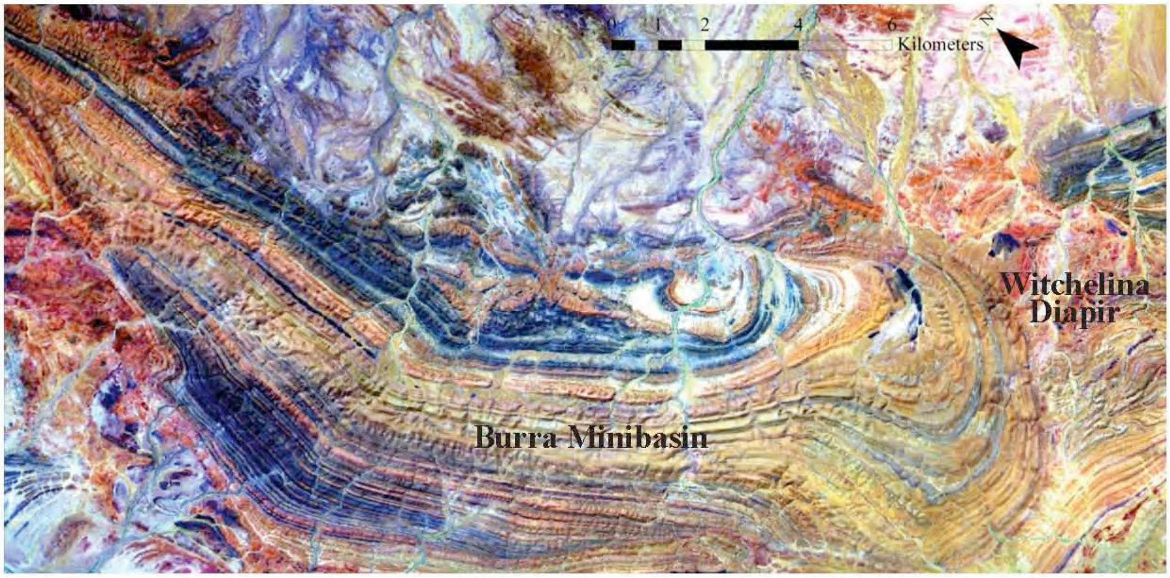

Hyperspectral imagery of the eastern Willouran Ranges, South Australia

SALT-SEDIMENT INTERACTION RESEARCH CONSORTIUM
(2012-2017)

Research Proposal
Outcrop, Seismic, and Margin-Scale Studies of Salt Diapirs, Welds, And Associated Minibasins

Submitted To: Joint Industry

Submitting Organization:

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Department of Geological Sciences
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Proposed Duration:

5 years (Phase I)
Starting Date: May 1, 2012
Ending Date: May 1, 2017

Proposed Annual Fee Per Company: $45,000/year

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EXECUTIVE SUMMARY

SALT-SEDIMENT INTERACTION RESEARCH CONSORTIUM
(2012-2017)
Outcrop, Seismic, and Margin-Scale Studies of Salt Diapirs, Welds, and Associated Minibasins

Submitted by Dr. Katherine A. Giles
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Recent increased imaging capabilities from wide azimuth (WAZ) seismic surveys has led to significant advances in recognition of near-salt features and our understanding of halokinetic processes. However, many features, especially at the reservoir scale are still beyond seismic resolution. As a result, outcrop analog studies still provide the most reliable dataset for cataloging the range of near-salt features that may be encountered and for developing new, innovative, salt-related play concepts and reservoir-scale geologic models. The primary aim of the proposed consortium is to identify, characterize, and determine the origin of the wide range of different features that are found in near-salt settings and to determine the behavior of fluids in this critical, but enigmatic zone. From this information we can develop predictive models of near-salt facies patterns, stratal architecture, structure, and fluid flow and test models developed from subsurface datasets.

The goal of the proposed consortium sponsored research is to conduct geologic and fluid-flow studies in three well-exposed, accessible salt basins: 1) Paradox basin, western USA; 2) Willouran and Flinders ranges of South Australia: and 3) Basque Pyrenees of northeastern Spain. These areas contain exceptional exposures of a variety of types of salt diapirs, salt welds, and minibasins where the scale and geometry of structural and stratigraphic features created by salt-sediment interaction can be examined in both plan view and cross section. The salt bodies and salt-related structures in these basins are important because high-quality, accessible exposures of salt-influenced basins are uncommon in the world, yet provide the only "ground truth" data, which can be used to define and calibrate the quality, geometry, and continuity of salt-related hydrocarbon traps and aid in predrill prediction and assessment of potential drilling hazards. In addition to the outcrop analog studies, the research team will also examine subsurface examples using 3-D seismic and well data around diapirs and allochthonous salt in the northern Gulf of Mexico. More regional projects will investigate the role of salt in the northern Spanish passive margin and the influence of crustal attenuation on evaporite deposition and subsequent salt tectonics.

The primary focus of the research team will be to document the geometry, geologic characteristics, and origin of features encountered at the salt-sediment interface or within salt diapirs. These features include: halokinetic growth strata, carapace strata, shale sheath, rubble zone, megaflap strata, caprock, and other non-halite intrasalt lithologies. The specific objectives of the research team are to document and to characterize the:

1) variation in geometry and sedimentology of halokinetic sequences/composite halokinetic sequences at different structural levels and at different types of diapirs, welds, and minibasins and determine the controls on the variation.
2) styles of basin-fill in primary and secondary minibasins and determine controls on the patterns.
3) structural, sedimentologic, and stratigraphic attributes of minibasins associated with different types of allochthonous salt bodies with emphasis on correlation and comparison of coeval suprasalt and subsalt minibasin stratigraphic assemblages.
4) distribution and nature of deformation, rubble zones, and salt-sediment interaction beneath salt sheets.
5) style, distribution and intensity of small-scale brittle deformation on the flanks of different types of salt diapirs and welds with the intent to determine controls on the differences.

6) nature and history of fluid flow in near-salt areas.
7) nature, distribution, origin, and history of caprock assemblages and non-evaporite lithologies within diapirs.
8) influence of different stages of crustal thinning and attenuation on evaporite deposition and subsequent deformation.

A diverse research team (refer to Appendix C for CV's) has been assembled to investigate the broad range of salt-related research topics. Drs. Kate Giles and Rip Langford and their graduate students and post-doctoral researchers at The University of Texas-El Paso will focus on sedimentologic, stratigraphic, and structural aspects. Dr. Mark Rowan (Rowan Consulting Inc.) will act as the salt tectonics/structural advisor for outcrop projects and for seismic analysis. Dr. Mark Fischer and his students at Northern Illinois University will coordinate structural and fluid-flow analysis. Thomas Hearon, (Doctoral candidate under Dr. Bruce Trudgill at Colorado School of Mines), will focus on the study of allochthonous salt emplacement and weld-seal issues utilizing data from all three salt basins and seismic datasets. Drs. Josep-Anton Muñoz and Eduard Roca and their graduate students at University of Barcelona will perform structural analysis of the Spanish diapirs. Dr. Carl Fiduk (WesternGeco) will assist in seismic and well analysis of subsalt deformation. We will also work in tandem with Dr. Andrew Hanson at University of Nevada, Las Vegas, who has organized an independent consortium focusing on the thermal history and hydrocarbon system in the Paradox Basin and Spanish Pyrenees field areas.

Results from this consortium research effort will benefit companies exploring and producing in onshore to deep-water offshore provinces in salt basins worldwide. Companies will gain invaluable predictive strategies for determining trap styles and reservoir compartmentalization in diapir-flank traps, developing new play concepts in salt-related petroleum systems, predicting fluid-flow patterns near vertical and inclined salt bodies and welds, and the nature and distribution of suprasalt, intrasalt, and subsalt potential drilling hazards. The research team will provide custom guided field trips to the respective research areas exclusively for sponsoring companies for a modest fee. These fieldtrips can serve as training programs for both novice and expert scientists working in salt basins or a venue for more focused group workshops. Furthermore, company sponsorship of the Salt-Sediment Research Consortium provides financial support and unprecedented training opportunities in many aspects of salt tectonics to both undergraduate and graduate students involved in the research effort and prepares them for productive industry careers.

The subscription fee for the Salt-Sediment Interaction Consortium is $45,000 per year for a five-year period (2012-2017). The annual research fee will be used primarily to support field logistics for the research team and research stipends for the students and postdocs. Annual deliverables for subscription include:

1) A 1-2 day formal meeting, in which yearly research results are presented.
2) Participation of up to three of your company's employees on a field trip in conjunction with the annual meeting (April or May) to view research localities in the Paradox Basin, Utah. The fieldtrip will showcase the salt structures and will evolve each year with new data. The field trip will include a guidebook containing maps, cross sections, field and laboratory photographs, and other data sets compiled as part of this research effort.
3) Access to our password protected website, which contains preprints & published research publications, meeting abstracts, student theses, meeting powerpoint presentations, and field guidebooks available to download.
4) Qualification of your company for private, custom-designed fieldtrips led by members of the research team to the respective field areas.

RESEARCH PROPOSAL

Outcrop, Seismic, and Margin-Scale Studies of Salt Diapirs, Welds, and Associated Minibasins

The proposed research has three components: outcrop studies, seismic studies, and margin-scale studies. Of these, the outcrop studies will be the principal focus of students and senior researchers, with the seismic and margin-scale studies being secondary.

Recent increased imaging capabilities from wide azimuth (WAZ) seismic surveys has led to significant advances in recognition of near-salt features and our understanding of halokinetic processes; however, many aspects are still beyond seismic resolution. As a result, outcrop analog studies still provide the most reliable dataset for cataloging the range of near-salt features that may be encountered and for developing new, innovative, salt-related play concepts and reservoir-scale geologic models. The primary aim of the proposed consortium is to identify, characterize, and determine the origin of the wide range of different features that are found in near-salt settings and to determine the behavior of fluids in this critical, but enigmatic zone. From this information we can develop predictive models of near-salt facies patterns, stratal architecture, structure, and fluid flow and test models developed from subsurface datasets.

We plan to conduct geologic and fluid-flow studies in three well-exposed, accessible salt basins: 1) Paradox basin, western USA; 2) Willouran and Flinders Ranges, South Australia; and 3) Basque and Central Pyrenees, northern Spain. These areas contain exceptional exposures of a variety of types of salt diapirs, salt welds, and minibasins where the scale and geometry of structural and stratigraphic features created by salt-sediment interaction can be examined in both plan view and cross-sectional view. The salt bodies and salt-related structures of these basins are important because high-quality, accessible exposures of salt-influenced basins are uncommon in the world, yet provide the only "ground truth" data which can be used to define and calibrate the quality, geometry, and continuity of salt-related hydrocarbon traps and aid in predrill prediction and assessment of potential drilling hazards.

The primary focus of the research consortium will be to document the geometry, geologic characteristics, and origin of features encountered at the salt-sediment interface or within salt diapirs. These features include: halokinetic growth strata, carapace strata, shale sheath, rubble zone, megaflap strata, caprock, and other non-halite intrasalt lithologies. The exceptional three-dimensional exposures in these basins offer a rare opportunity to:

- examine the nature of the salt-sediment interface,
- document the geometry, sedimentology, and structural deformation of growth strata associated with diapiric rise and subhorizontal extrusion in a wide range of depositional environments including fluvial/lacustrine, shelfal tidal, deltaic and reefal, and basinal turbidite depositional systems in both siliciclastic and carbonate dominated systems,
- evaluate the stratigraphic evolution and depositional partitioning of the basins through time,
- examine the nature of different types of welds in terms of their origin and evolution and their influence on migration and seal,
- determine the nature and origin of caprock assemblages and other intradiapir, non-halite lithologies.

The second major goal of the research consortium will be to supplement the outcrop studies with analysis of appropriate seismic datasets and associated well data. We already have access to a modern 3-D seismic volume over a vertical diapir in the slope of the northern Gulf of Mexico. This will allow us to test aspects of halokinetic deformation that cannot be determined from outcrops, specifically the lateral and vertical variations in near-diapir deformation and the relationships between halokinetic sequences and deepwater depositional sequences. We will also seek access to data that will allow us to compare subsalt geometries and deformation to those observed in South Australia in order to develop more refined and predictive models of salt emplacement and associated salt-sediment interaction.

A third, albeit subsidiary, goal of the research consortium will be to examine certain aspects of salt-bearing passive margins. Our field areas in Spain are part of an Atlantic margin that was later inverted during the Pyrenean Orogeny. We will use outcrop, seismic, and well data to examine the role of salt in controlling basin-scale geometries and processes associated with thick-skinned extension and crustal attenuation, thin-skinned gravity gliding, and later contraction. We will also extend our work to a more general analysis of salt in the context of modern ideas of passive margins, specifically how different stages in the development of hyperextended margins influence evaporite deposition and subsequent salt tectonics.

Research Objectives

Field Component

The field component of the proposed consortium research will address 6 fundamental objectives and builds on halokinetic sequence concepts developed primarily from previous field studies in NE Mexico, which are no longer safely accessible (refer to Appendix D for Giles and Rowan, 2012, Geological Society of London paper summarizing our current understanding of halokinetic sequences). For each of the following objectives we briefly summarize the current thinking drawn from previous studies, followed by a list of questions on that topic that we plan to specifically address as part of this research effort. We will collect field data from appropriate areas in the 3 outcropping salt basins in order to test proposed hypotheses and meet the following objectives:

Objective 1

Document the variation in geometry and sedimentology of halokinetic sequences and composite halokinetic sequences at different structural levels and at different types of diapirs, welds, and minibasins and determine the controls on the variation.

Near-diapir strata are typically organized into halokinetic sequences (Giles and Lawton; 2002; Rowan et al., 2003). Halokinetic sequences are successions of drape-folded strata bounded by angular unconformities adjacent to diapirs and are genetically related to passive diapirism (Figure 1). We interpret halokinetic sequences as forming in response to variations in the rate of net diapiric rise relative to net sediment accumulation. We recognize two end-member types (Figure 2) of sequences (Hook and Wedge) that vary in depositional facies progression, relative sediment-accumulation rates, stratal geometry and width of the zone of halokinetic deformation. Hook halokinetic sequences (Figure 2a) are typically composed of a basal debrite lithofacies of material locally derived from the diapir roof or the diapir itself. The debrites are of local extent and are typically interbedded with and overlain by shale-prone lithofacies representing slow sediment-accumulation rates relative to rise rates of the diapir. Tight drape folding close to the diapir (maximum 200 m) results in near vertical bedding dips and local 90^{o} angular unconformities. In contrast, wedge halokinetic sequences (Figure 2b) typically lack mass wasting deposits and diapir-derived detritus. They contain lithofacies representing higher sediment-accumulation rates, a broad zone of drape folding extending up to 1 km from the diapir, and angular unconformities of less than 30^{o}.

Halokinetic sequences stack into 2 types of composite sequences (Tabular and Tapered; Giles and Rowan, 2012) with distinctive stratal geometries (Figure 3) that are increasingly recognizable on modern seismic data (Figure 1). Tabular composite halokinetic sequences (Tabular-CHS) form by stacking hook sequences, which creates a large-scale package with a tabular form (top and bottom boundaries are roughly parallel) where all the thinning and upturn of individual sequences is within less than 200 m of the diapir (Figure 3a). Tabular-CHS form during periods of overall slow sediment-accumulation rates relative to diapir-rise rates. Tapered composite halokinetic sequences (Tapered-CHS) form by stacking wedge sequences, which creates a large-scale package with a folded tapered form (top and bottom boundaries are convergent toward the diapir). The bottom boundary is folded over

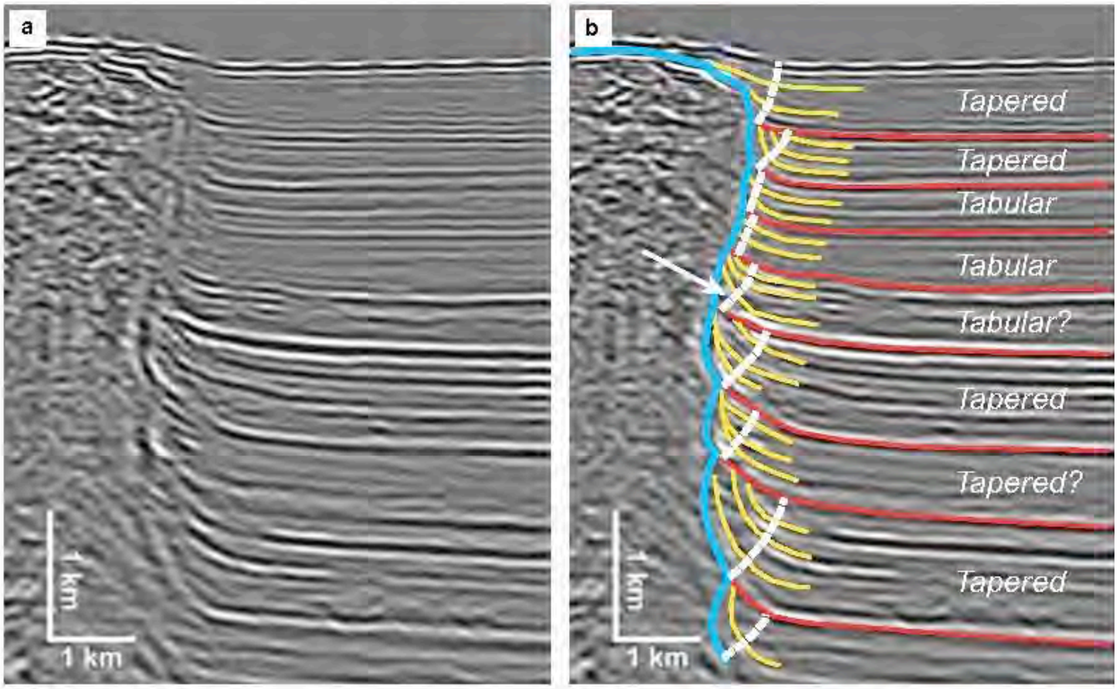


Figure 1. Prestack depth-migrated seismic profile (reverse-time-migration sediment flood) of a secondary diapir and flanking strata from the northern Gulf of Mexico: (a) uninterpreted and (b) interpreted. The diapir edge is cuspate and stacked unconformities (red) define variably folded halokinetic sequences identified as tapered or tabular CHS. White dashed lines are axial traces of halokinetic folds and the white arrow indicates a wedge-shaped body tentatively identified as a mass-wasting deposit. Vertical exaggeration 1.5:1. Seismic data courtesy of C. Fiduk and CGGVeritas.

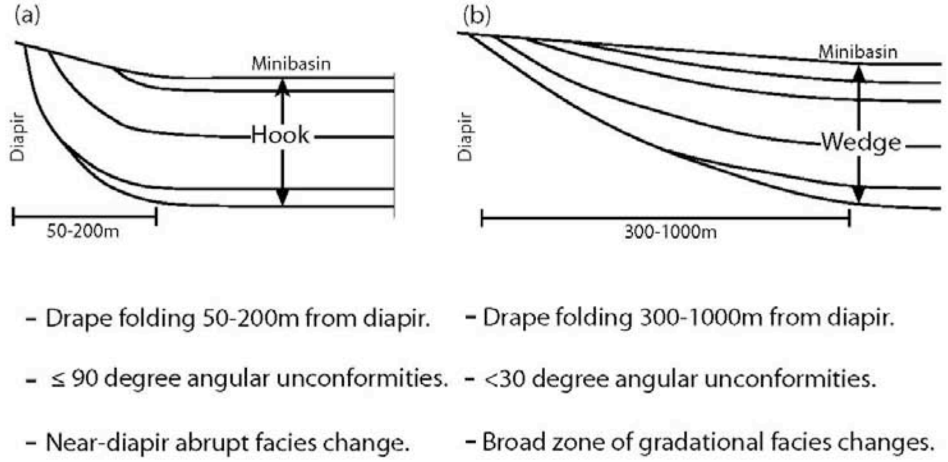


Figure 2. Two end-member types of halokinetic sequences: a) hook halokinetic sequence; and b) wedge halokinetic sequence. From Giles & Rowan (2012).

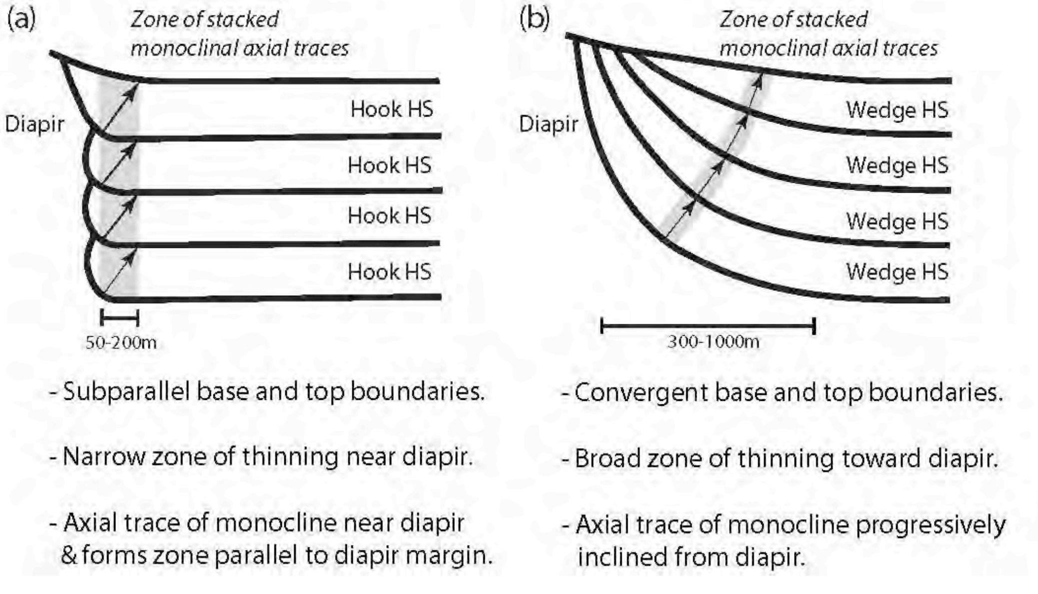


Figure 3. Two end-member types of composite halokinetic sequences (CHS): a) tabular CHS; and b) tapered CHS. From Giles & Rowan (2012).

a distance of 300-1000m from the diapir (Figure 3b). Tapered-CHS form during periods of overall high sediment-accumulation rates relative to diapir-rise rates. A Tapered-CHS overlying another Tapered-CHS creates a salt cusp at the edge of the diapir, whereas a Tabular-CHS overlying a Tapered-CHS does not create a cusp.

Halokinetic sequences stack into 2 types of composite sequences (Tabular and Tapered; Giles and Rowan, 2012) with distinctive stratal geometries (Figure 3) that are increasingly recognizable on modern seismic data (Figure 1). Tabular composite halokinetic sequences (Tabular-CHS) form by stacking hook sequences, which creates a large-scale package with a tabular form (top and bottom boundaries are roughly parallel) where all the thinning and upturn of individual sequences is within less than 200 m of the diapir (Figure 3a). Tabular-CHS form during periods of overall slow sediment-accumulation rates relative to diapir-rise rates. Tapered composite halokinetic sequences (Tapered-CHS) form by stacking wedge sequences, which creates a large-scale package with a folded tapered form (top and bottom boundaries are convergent toward the diapir). The bottom boundary is folded over a distance of 300-1000m from the diapir (Figure 3b). Tapered-CHS form during periods of overall high sediment-accumulation rates relative to diapir-rise rates. A Tapered-CHS overlying another Tapered-CHS creates a salt cusp at the edge of the diapir, whereas a Tabular-CHS overlying a Tapered-CHS does not create a cusp.

Thick Tapered-CHSs are ubiquitous during early diapiric rise and primary minibasin formation. We suggest that this results from there being minimal differential sediment load driving salt flow from the autochthonous level so that even though salt-rise rate is slow, relatively low sediment supply still outpaces diapiric rise. Patterns at higher levels on diapirs are more complex. In shelf settings, Tabular-CHSs commonly form during periods of low sediment flux, which is typical of 3rd-order transgressive systems tracts, whereas Tapered-CHSs typically form during periods of higher sediment influx such as the highstand systems tract. In deepwater settings, where the bulk of deposition occurs during the lowstand systems tract, deeper Tapered-CHSs tend to transition upward to Tabular-CHSs because the increasing differential sediment load drives more rapid salt rise, although significant 3rd-order variations in sediment-accumulation rate may alter this pattern. In both settings, shortening of diapirs at any time increases salt-rise rates so that Tabular-CHSs are dominant.

Questions to be addressed:

1) We've identified different end-member types of composite halokinetic sequences. Are there variations on the types that have important implications for origin and development of the composite sequence and prediction of distribution of sedimentary facies within the sequences?
2) In ramping salt sheets and steep diapirs does the apparent abrupt shift in the position of the axial trace of drape-fold monoclines (Figure 1) always correspond to composite halokinetic sequence boundaries? If so, what's changing in the dynamics of the salt-sediment system between CHSs? Is it just thickness of the roof or are there other factors?
3) What is the forcing mechanism that initiates periods of major erosion of the diapir roof strata and formation of CHS boundaries? Is there a feedback loop between diapir-top erosion and diapir rise/salt-sheet break out, similar to the feedback loops proposed for increased uplift rates of mountain belts in areas of increased erosion (Berger et al., 2008; Whipple, 2009; Malavieille, 2010)
4) Our previous studies utilized field exposures in shelf depositional settings in primary minibasins. How well do our findings and models apply to deepwater settings? We will analyze depositional attributes of Cretaceous turbidites in the Spanish outcrops and Neoproterozoic-Cambrian turbidites in subsalt and suprasalt minibasins in the Flinders Ranges to determine controls on CHS style and facies distribution of the turbidite systems deposited around diapirs.
5) How do turbidite facies architecture and distribution patterns, both spatially and temporally, relate to halokinetic sequence and composite sequence type? Are there predictable patterns of reservoir distribution?

6) Where in the composite halokinetic sequence stratigraphy do debrites and mass transport complexes (MTC) tend to form? Are they typically at the base directly above the halokinetic sequence boundary? What are the geometry, distribution and sedimentology of the MTCs? Do different types of MTCs form in different parts of halokinetic sequences or composite sequences? What is the source(s) of the MTC material? What are specific controls on the formation of MTCs and their distribution? How do turbidites and channel complexes relate to MTC facies both spatially and temporally?

Objective 2

Document the styles of and determine controls on basin-fill patterns in primary and secondary minibasins.

The lower portions of minibasins often contain broad areas of folding and thinning somewhat analogous to Tapered-CHSs. In some cases, stratal packages known as megaflaps extend far up the side of the minibasin (Figs. 4, 5), and in suprasalt minibasins, basal carapace may be present (Fig. 6). We plan to use outcrops in both South Australia and Spain to examine these features and their relationships to composite halokinetic sequences.

Questions to be addressed:

1) Long-term rates of salt rise are inferred to increase as differential load caused by an increasingly thick sedimentary overburden grows with time. Therefore, minibasins developed on allochthonous salt might begin to grow in a manner similar to those above autochthonous salt. Is this indeed the case, or are there key differences between the two levels?
2) Do halokinetic sequence types in primary and secondary minibasins evolve through a predictable historical succession?
3) How common are carapace blocks and megaflaps in the base of secondary minibasins? Are secondary megaflaps just rotated carapace? If so, how do they differ from primary megaflaps?
4) How do suprasalt minibasin halokinetic sequence stratigraphy and basin-fill patterns correlate to their subsalt minibasin counterparts. Are there attributes that can be mapped in the more readily imaged suprasalt minibasin that can provide a predictive model of what can be expected in the typically poorly-imaged correlative subsalt minibasin.
5) Hudec et al. (2009) have proposed a number of mechanisms for secondary minibasin initiation in the northern Gulf of Mexico. Do we see evidence supporting these models or do they need to be modified?

Objective 3

Document the structural, sedimentologic, and stratigraphic attributes of allochthonous salt emplacement with emphasis on prediction of subsalt features at the salt-sediment interface.

We have started detailed field mapping of units associated with climbing allochthonous salt, salt break out, coalescing salt sheets and suture zones in the Willouran Ranges and at Pinda, Patawarta, Oladdie, and Loch Ness diapirs in the Flinders Ranges, South Australia (Figure 8). Key observations of subsalt relationships at the different diapirs in correlative strata can be used to constrain models of allochthonous salt emplacement (Hearon et al., 2010; Kernen et al., 2012), controls on salt breakout and to predict subsalt structures and facies. Our preliminary observations are:

1) sheared strata are absent,
2) preserved thrust faults are rare,
3) strata are commonly folded and thinned beneath base-salt ramps,

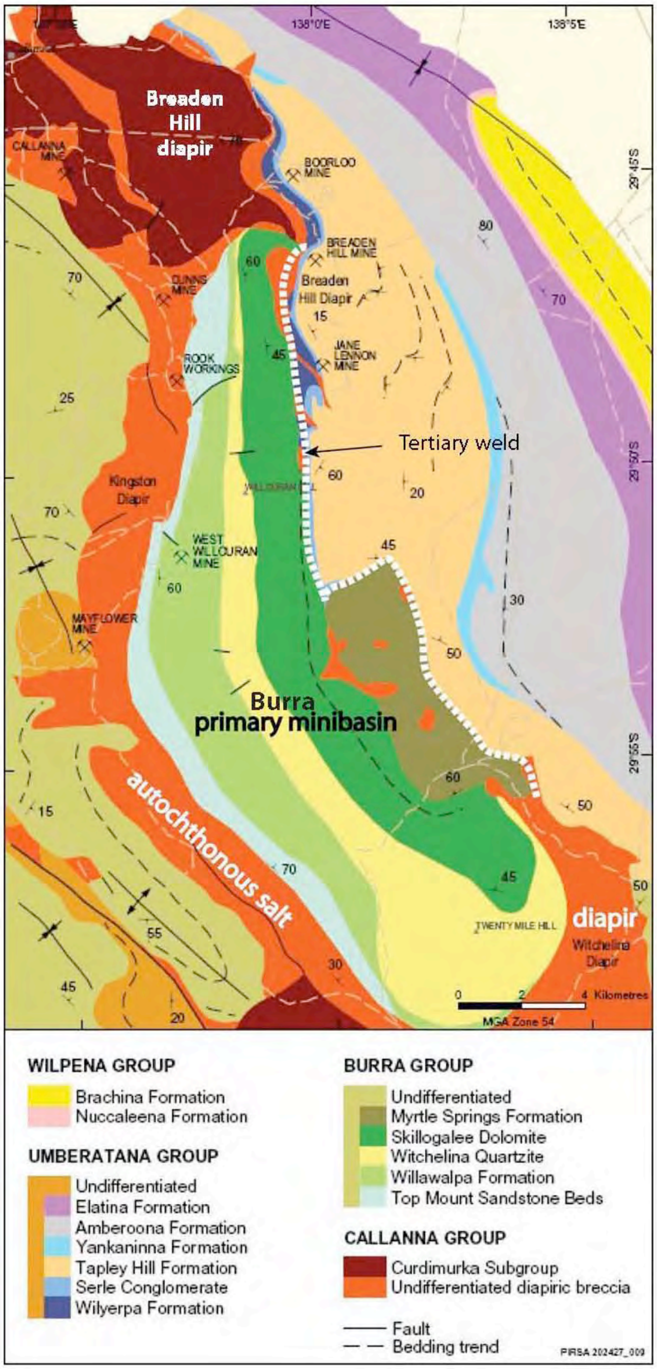


Figure 4a. Geologic map of Breaden Hill diapir and Burra primary minibasin in the Willouran Range, South Australia. Modified from Dyson (2004); after Forbes & Coats (1963), and Forbes (1990)

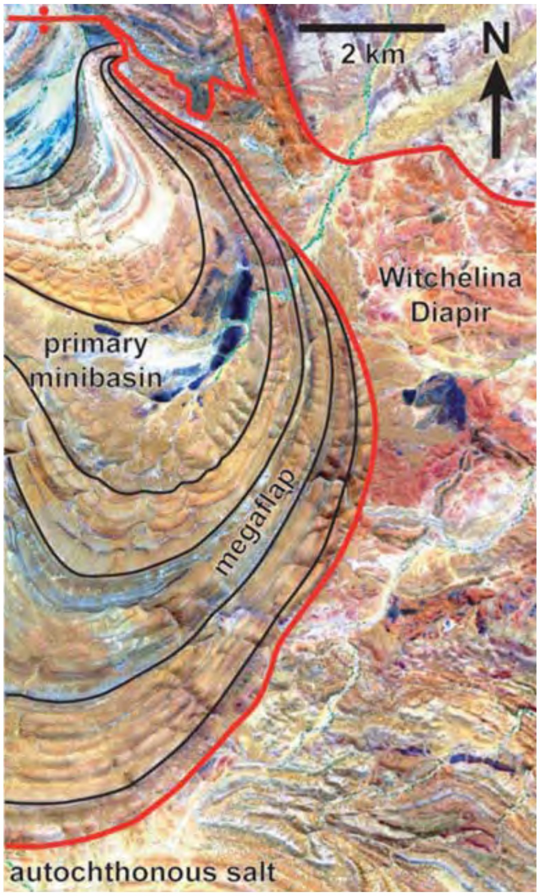


Figure 4b. Hyperspectral image of the Witchelina Diapir in the Willouran Ranges of South Australia. From Giles and Rowan (2012).

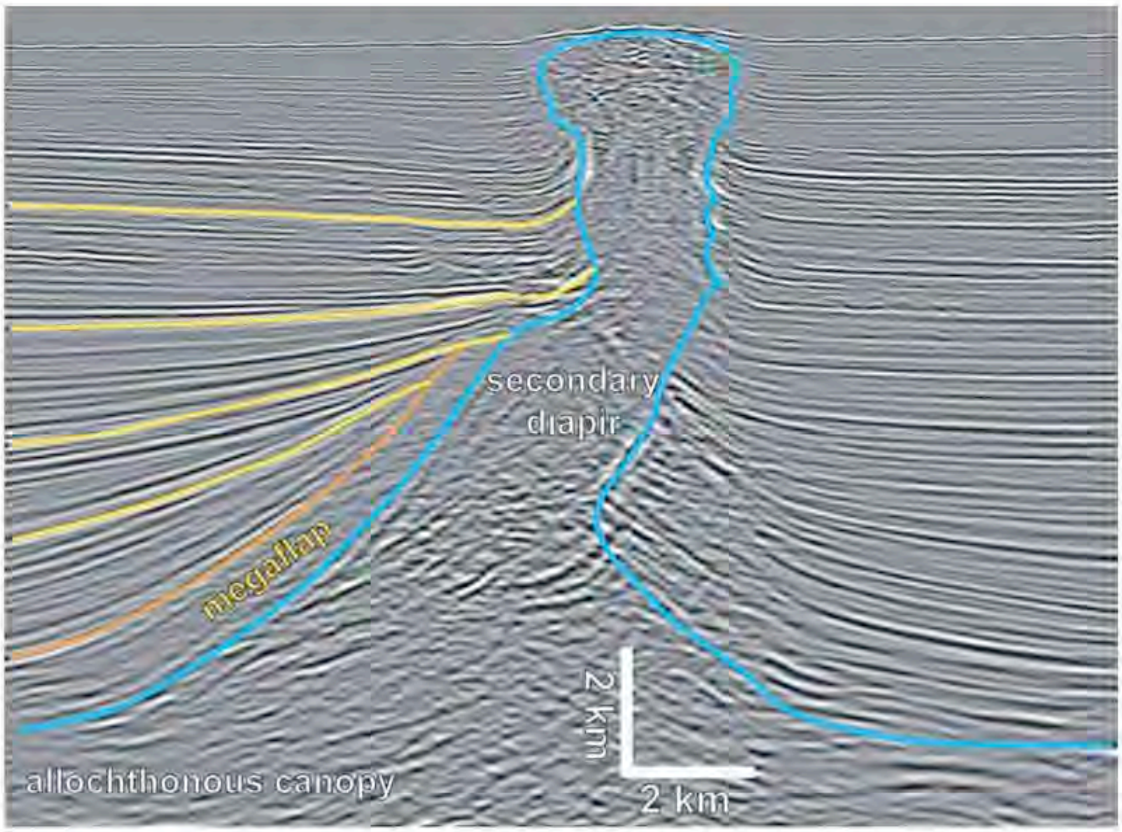


Figure 5. Prestack depth-migrated seismic profile (reverse-time migration sediment flood) of the same diapir from the northern Gulf of Mexico illustrated in Figure 8. The left minibasin has a basal megaflap that is draped along the diapir flank and onlapped by a growth wedge of younger minibasin strata. Note the local halokinetic folding at higher levels of the diapir. No vertical exaggeration. Seismic data courtesy of C. Fiduk and CGGVeritas.

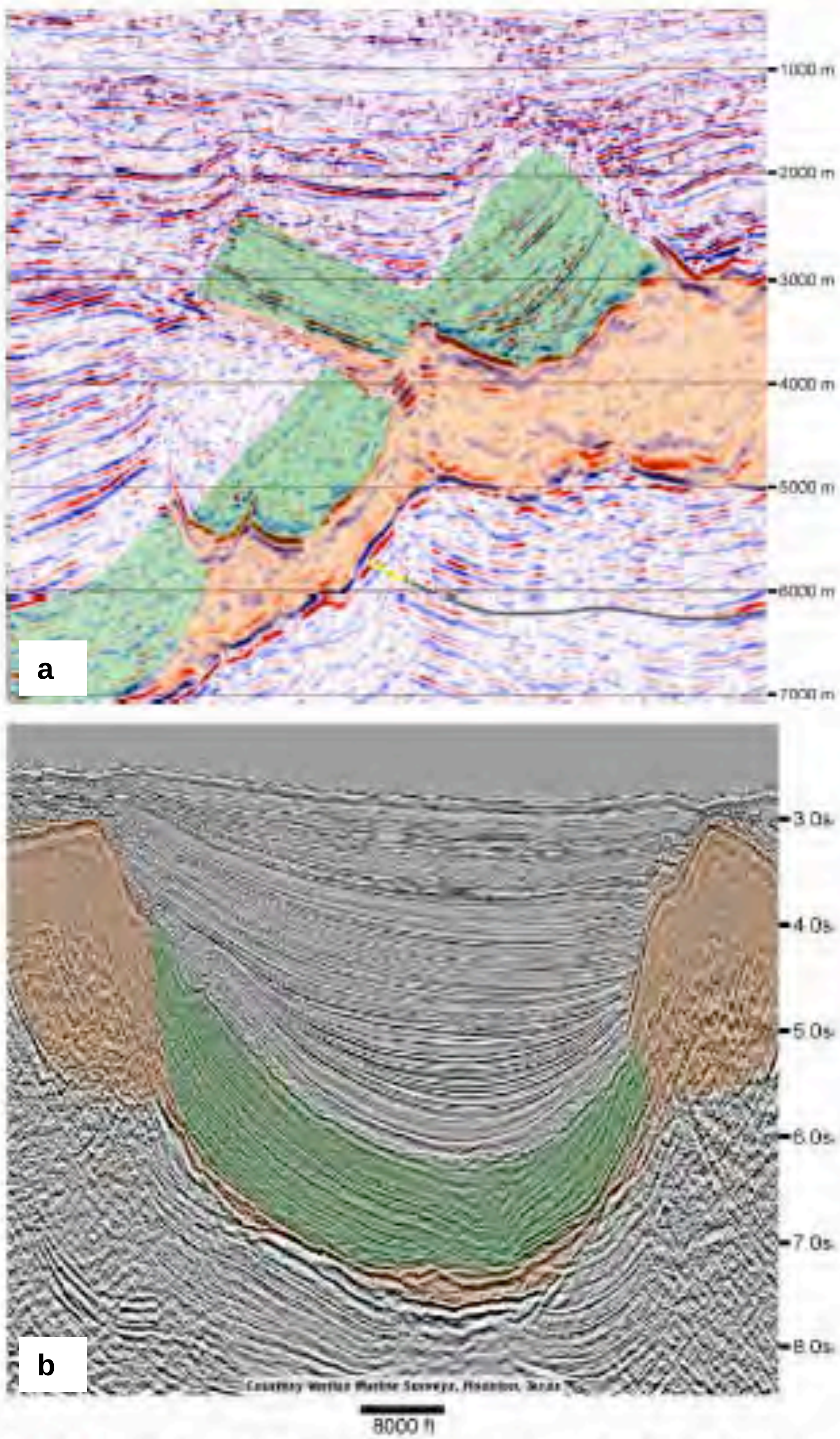


Figure 6. Stratal Carapace expression on seismic datasets.
a. Disjointed carapace segments perched above a complex salt allochthon. From Hart et. al. (2004).
b. Sub-surface stratal carapace conforming to the base of a suprasalt minibasin. From Hart et. al. (2004).

1) discrete mass-transport complexes (MTCs) or turbidites containing diapir-derived detritus and/or blocks of carapace are locally intercalated with normal minibasin strata at halokinetic sequence boundaries, and
4) extensive folded caprock assemblages may be present and confined to discrete stratigraphic intervals. These observations suggest that a halokinetic-sequence model for allochthonous salt emplacement, which invokes variable drape folding and slump failure of surficial scarps, is more suitable than a basal-shear model (Harrison and Pattison, 1995; Harrison et al., 2004), in which there is a subsalt zone of sheared strata, or an accretionary-wedge model (Hudec and Jackson, 2009), wherein salt commonly overrides imbricate thrust faults.

Questions to be addressed:

1) What is the range of lithofacies, stratal geometries, and structures encountered just beneath allochthonous salt? Is there a way to predict what will be encountered utilizing relationships from strata away from diapirs or in correlative suprasalt minibasins that may be more readily imaged on seismic datasets.
2) In ramping salt sheets, preliminary observations from South Australia suggest that Tapered-CHSs are the most common. Are there any examples of hook halokinetic sequences or Tabular-CHSs? If so, what are the variables controlling halokinetic sequence type? If Tabular-CHSs are rare, what does that tell us about the dynamics of salt sheet movement? And why is there sometimes no halokinetic deformation at all?
3) Previously we focused on ramping salt sheets, but we will now investigate base-salt flats more explicitly. What are the structural features associated with flats? Is there any sort of subsalt folding or thrusting? Are MTC's present beneath base-salt flats? If so, how do they compare to those found in ramp settings in regard to sedimentology, structure, and halokinetic sequence stratigraphy?
4) What are the sedimentologic, stratigraphic, and structural relationships between suprasalt minibasins, carapaces, and sub-salt flanking strata?
5) A critical transition in salt sheet behavior is the ramp-flat and flat-ramp transition. Are there sedimentologic and structural features in flanking strata that characterize this transition? What factors, such as sediment-accumulation rates or mechanisms of salt sheet advance, cause sheets to cease ramping and extrude more horizontally and vice-versa? Are there recognizable sedimentologic or stratigraphic features formed in the coeval suprasalt strata during transitions that could help constrain possible mechanisms for sheet movement?
6) Another critical transition area is the zone of thrust breakout on a pinned, inflated salt sheet. What controls the break-out point on the drape-fold monocline? Why is more of the drape-fold monocline preserved in the subsalt minibasin margin in areas like at Patawarta and Pinda diapirs, SA where as in other instances no drape fold is preserved and strata trend transversely into the margin of the ramping diapir such as at Oladdie diapir.

Objective 4

Document and summarize mesoscopic deformation patterns in the vicinity of different types of salt diapirs and welds, with the intent to determine controls on the differences.

Mesoscopic deformation patterns are defined by the style, orientation, distribution and dimensions of features such as faults, joints, cleavage, deformation bands, and bedding-slip surfaces throughout a rock volume. Depending on their timing, these features can play a significant role in fluid migration and storage. Our research to date has focused on La Popa Basin (Fig. 7), where we have characterized the deformation patterns around El Papalote diapir and La Popa weld (Rowan et al., 2003; Smith, 2010, Rowan et al., 2012; Smith et al., 2012). Deformation along La Popa weld varies according to stratigraphy, structural position, and the amount of remnant evaporite in the weld zone. Brittle fractures are most abundant in sandstones along the downthrown side of the weld, and near a significant bend in the map-view trace of the weld (Fig. 7). Fractures are also more abundant where welding is complete and there is little to no evaporite in the weld zone. Deformation intensity in weld-adjacent rocks appears to correlate with halokinetic sequence style, wherein Tabular CHSs contain more brittle deformation features than Tapered CHSs. Around El Papalote diapir fractures occur in one of three orientations: (1) bed-parallel, (2) bed-perpendicular and parallel to local bedding strike, and (3) bed-perpendicular and perpendicular to local bedding strike. The abundance for all these sets is generally low, but deformation is weakly partitioned into siltstones and carbonates. Halokinetic sequence boundaries around the diapir are often the sites of concentrated brittle deformation, and the majority of fractures appear to have formed during diapir rise, coincident with upturning of diapir-adjacent strata.

The next phase of our research will build on results from La Popa Basin, Mexico, and is aimed at understanding the links between deformation patterns and hydrologic behavior of rocks in the vicinity of welds and diapirs. Information on the evolution of deformation-induced porosity and permeability will be more closely integrated with halokinetic sequence stratigraphy to ascertain whether there are any reliable correlations on which one might develop predictive models of reservoir deformation and quality. Work on welds will focus on the Flinders Ranges, where vertical welds are exposed at Loch Ness and Nuccaleena diapirs, an inclined, counter-regional-style weld developed above a remnant salt pedestal at Oladdie diapir (Dyson and Rowan, 2004), and a multi-level allochthonous, or tertiary weld juxtaposing different-aged strata in the eastern Willouran Ranges (Figure 4). In addition to our continuing work on diapirs in the Flinders Range, new work on deformation patterns around diapirs will include the Bakio and Bermeo structures along the northern coast of Spain, as well as the Onion Creek diapir in the Paradox Basin.

Questions to be addressed

1) Does the style, distribution and intensity of mesoscopic brittle deformation systematically vary amongst primary, secondary and tertiary welds? In addition to weld style, how important is weld geometry (e.g., bends, cusps, etc.) in controlling deformation patterns in weld-adjacent rocks?
2) What is the timing of brittle deformation relative to weld formation? Does most of the deformation adjacent to welds occur prior to welding, when there is still substantial salt along the weld, or does most deformation accumulate after evacuation of the weld? Is there some critical thickness of salt that causes deformation to be preferentially partitioned into the salt or into the weld-adjacent rocks?
3) What is the relative significance of pre- and post-welding deformation in controlling deformation patterns around welds?
4) Is there any correlation between intensity and style of deformation and the geometry of the salt-sediment interface? In other words, how does the deformation vary between vertical diapirs, allochthonous base-salt ramps, and allocthonous base-salt flats?
5) Do deformation patterns vary according to the depositional setting of diapirs? For example, do diapirs developed in alluvial, subaerial settings such as the Paradox Basin develop markedly different deformation patterns than those developed in deep-water turbidite settings like those of the Cantabrian Basin?
6) Is there a relationship between halokinetic sequences and reservoir quality near diapirs. If such a relationship exists, does it correlate with variables like depositional setting, diapir size, or depth of diapir emplacement?

Objective 5

Characterize the nature and timing of fluid flow in the vicinity of diapirs and welds, and in particular, at the salt-sediment interface.

Our previous studies focused on fluid and hydrocarbon systems near La Popa weld and El Papalote diapir (Fig. 7). Collaboration with Dr. Andrew Hanson (UNLV) led to the identification of migrated hydrocarbons along La Popa weld and a vitrinite-based burial history curve for La Popa Basin (Hudson and Hanson, 2010). When combined with fluid inclusion, stable isotopic and strontium isotopic work,

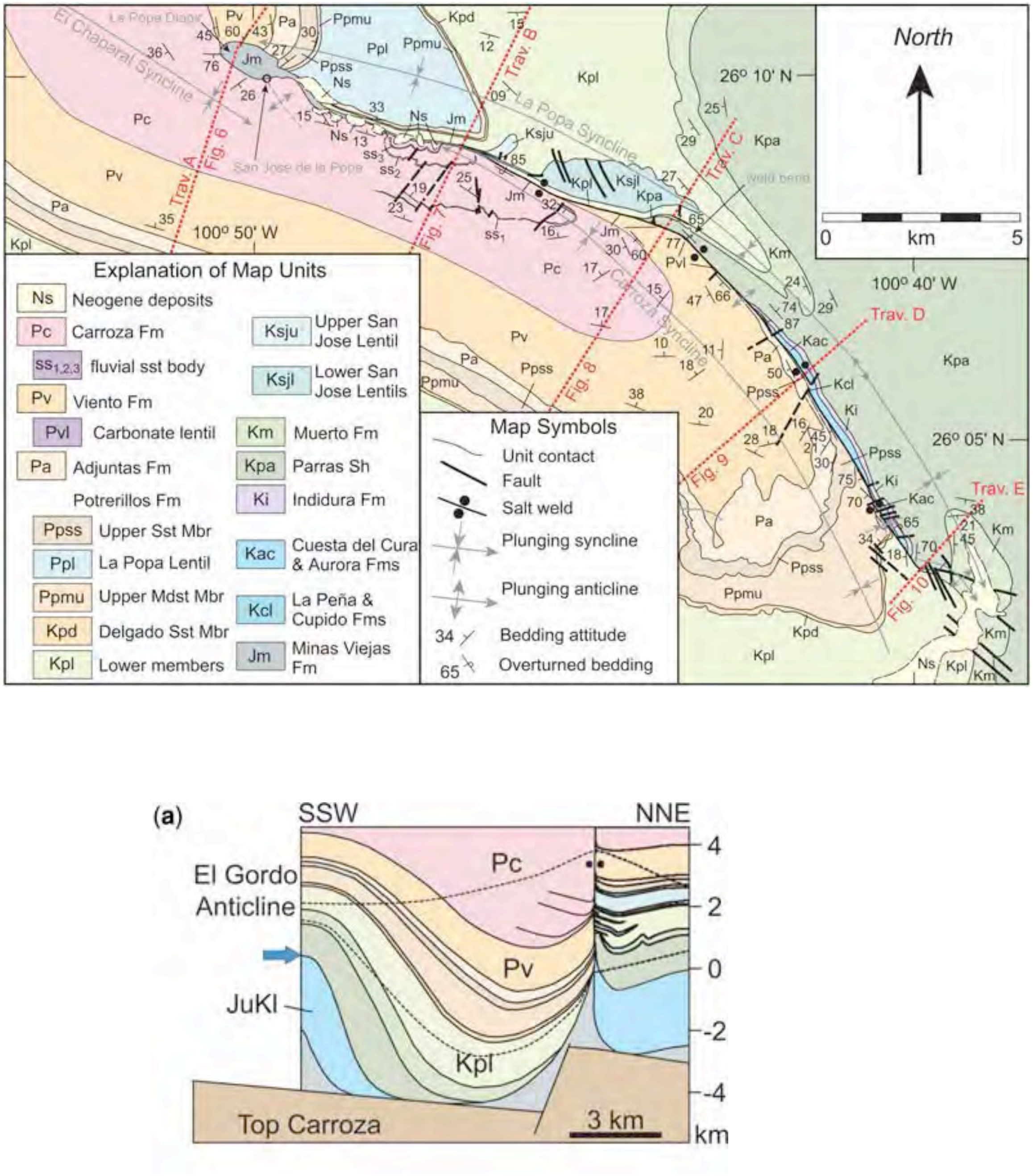


Figure 7. Geologic map (a) and cross section (b) of La Popa weld and surrounding strata in La Popa Basin, northeast Mexico. Modified from Rowan et al., 2012).

these results allowed us to develop detailed models of the fracture-controlled hydrologic systems near La Popa weld and El Papalote diapir (Smith, 2010, Smith et al., 2012). La Popa weld served as a vertical fluid conduit and a lateral fluid baffle. Fluids of several different compositions and temperatures from 100° to 200℃ migrated along the weld, with migration concentrated near the map-view bend near the weld center. Methane and degraded hydrocarbons found in fluid inclusions in calcite veins along the weld were most likely sourced from the downthrown side of the weld in the Potrerillos or Parras formations. Although some fractures may have formed prior to complete welding, burial history modeling suggests that fluid migration and the majority of fractures did not occur until after the majority of salt was evacuated from La Popa weld, in a period of Laramide-related shortening.

Our model for the fracture-controlled El Papalote fluid system is based on stable and strontium isotopic analyses, coupled with fluid inclusion analysis of veins in the vicinity of the diapir (Smith, 2010). Although the data are limited, stratigraphic variability in fluid compositions and temperatures suggests the El Papalote fluid system may have been vertically partitioned into cells related to halokinetic sequences. Shallower sequences contained less saline and cooler fluids that appear not to have interacted with rocks below the Delgado Sandstone. Deeper sequences contained methane, as well as warmer and more saline fluids that were derived from deeper in the basin. The diapir-related fluid system appears to have been relatively small, extending less than a kilometer away from the salt-sediment interface.

In the next phase of our research we propose to expand our work on fluid systems around diapirs and welds. We will integrate detailed stratigraphic studies with analysis of mesoscopic deformation to determine the controls and relative significance of structural and stratigraphic variables on fluid system structure and behavior. We will particularly focus on compartmentalization and the role that halokinetic sequence style and deformation interact to control fluid distribution in the vicinity of diapirs. As noted in Objective 4, we will characterize fluid systems around diapirs in a variety of depositional settings in the Paradox and Cantabrian Basins, as well as the Flinders Ranges.

Questions to be addressed:

1) Do the fluid systems around diapirs systematically vary according to depositional setting? For example, do diapirs in deepwater settings develop fluid systems that are different from those around diapirs in shelf and alluvial settings?
2) How do diapir-related fluid systems evolve during diapir emplacement?
3) What is the role of halokinetic sequence boundaries in vertically compartmentalizing fluid systems around diapirs?
4) Do diapirs produce a recognizable thermal signature in the nearby hydrologic system? If so, what is the spatial extent of that signature?
5) How does the development of caprock sequences affect the distribution and movement of fluids in the vicinity of diapirs?

Objective 6

Characterize the nature, distribution, and origin of layered caprock and non-halite lithologies within diapirs.

The presence of intrasalt lithoclasts and layered caprock presents potential drilling hazards and may complicate seismic processing procedures. Thus, a thorough understanding of the formation and entrainment of intrasalt lithoclasts and layered caprock is important. All of the diapirs in the studied outcropping salt basins contain lithoclasts of non-evaporite material and layered caprock assemblages have been identified in the Paradox basin and in South Australia, but not La Popa basin or in the Pyrenees. The Mexican diapirs contain Jurassic carbonate and metaigneous clasts. The Paradox Basin salt walls contain dolomite and black shale clasts and layered anhydrite and carbonate caprock in diapir-flanking positions (Shock, 2012). The Flinders and Willouran ranges autochthonous and diapiric salt contain a wide variety of siliciclastic lithologies along with carbonates and metaigneous clasts and layered carbonate caprock in both suprasalt and subsalt positions. The clasts in the salt sheets in the Flinders Ranges are enormous (ranging up to several km across) as are local layered caprock facies (Fig. 8). The Spanish diapirs contain clasts of mudstone and both volcanics and intrusives. In all four areas we (and others) have interpreted the intrasalt lithoclasts as representing lithologies originally interbedded with the evaporites or intruded into the evaporite basin, which become disrupted with the onset of diapirism and carried along in the flowing diapirs. The layered caprock is interpreted as forming by the processes of halite dissolution by undersaturated waters (leaving an insoluble residue of dominantly anhydrite) and microbial sulfate reduction from hydrocarbons (recrystallizing anhydrite to carbonate) at the top of the rising diapir.

Questions to be addressed:

1) Are the intrasalt lithoclasts only lithologies that were depositionally interbedded or intruded into the evaporite? We will document the age, lithology, and dimensions of intrasalt clasts in order to determine what units the clasts were derived from.
2) What is the distribution of clasts in the diapir? Is there a concentration of clasts in certain structural settings such as diapir margins versus cores, along weld surfaces, at flat to ramp transitions, or adjacent to thick layered caprock sequences? Are clasts concentrated at halokinetic sequence boundaries (i.e. associated with salt cusps)?
3) In Australia, do we have any examples of carapace pieces that have become incorporated into the canopy salt as one sheet over rides another, as is known from the GoM? If so, what are the characteristics of entrained carapace strata?
4) Are lateral/flanking caprock assemblages tied to discrete CHSs or do they transcend CHS boundaries? Are they tied to an end-member type of CHS?
5) Is there a documentable caprock stratigraphy that can be tied to the CHS stratigraphy. Are there specific times in the rise history of the diapir when caprock forms? If so what is controlling presence of caprock or not? Is it the CHS stratigraphy, the hydrocarbon maturation and migration history, or undersaturated fluid migration history possibly tied to relative sea level changes?

Seismic Component

The outcrop studies will be supplemented by analysis of relevant seismic datasets. Although field exposures allow us to examine features not observable on seismic data, the reverse is also true: seismic data provide a three-dimensional view generally not available in surface outcrops. Key questions can be answered only by combining analyses of both types of datasets.

Objective 1

Determine the lateral and vertical variations in halokinetic deformation and their relationships to deepwater depositional sequences.

We have already gained access to a modern, 3-D WAZ dataset over a vertical diapir in the northern Gulf of Mexico slope. Available volumes include Kirchhoff, WEM, and RTM migrations. In addition, we have well data and detailed biostratigraphic data. The interpretation will involve identifying diapir-flanking unconformities, the geometry and nature of the intervening composite halokinetic sequences, the role of near-diapir faults, and the relationship of the composite halokinetic sequences to deepwater depositional sequences.

Questions to be addressed:

1) Does halokinetic folding at the same stratigraphic level vary on different sides of the diapir? Is there any lateral transition between Tabular- and Tapered-CHSs and, if so, what is the nature of the transition? Is it gradual or abrupt?
2) How does composite halokinetic-sequence development vary with depth? Is there an upward transition from more Tapered CHSs to more Tabular CHSs as predicted by the models?
3) Where do CHS bounding unconformities fall within the depositional sequences? Do they effectively coincide with depositional sequence boundaries, as predicted, or are they more variable?
4) How do sediment-accumulation rates vary in the adjacent minibasins and how does this influence CHS style? Do Tabular CHSs and Tapered CHSs occur during times of slow and rapid deposition, respectively? Or is there another factor such as shortening that controls halokinetic deformation?
5) Are there systematic facies variations between different types of CHSs or within individual CHSs? Can these be related to variations in relative sea level?
6) How do the observed geometries and stratigraphic relationships compare with those at the exposed Bakio diapir in northern Spain and diapirs in South Australia? What might explain any differences?

Objective 2

Determine the controls on subsalt deformation and the spatial and thickness variations in subsalt rubble zones and generate a predictive model for the presence and nature of subsalt deformation.

Subsalt rubble zones are common in the northern Gulf of Mexico, where Kilby et al. (2008) showed its presence in 32 out of 37 wells. Yet field outcrops in Australia display no subsalt shear zones and no zones of disturbed strata just beneath salt except for occasional MTCs that interfinger with minibasin stratigraphy. Moreover, Tapered CHSs appear to be more common in South Australia than in the GoM, whereas only 3 of the 37 wells encountered coherent, overturned strata beneath salt (Kilby et al., 2008). Finally, subsalt thrust faults, although imaged in the GoM, are very rare in South Australia. Any thorough model for allochthonous salt emplacement and associated salt-sediment interaction must be able to explain these differences.

We plan on using modern seismic, well, and biostratigraphic data from the northern GoM to investigate the relationships between salt geometry, imbricate thrust development, and rubble zone development. Assuming that there are correlatable patterns, we will develop a general model and explain why allochthonous salt in the two basins behaved differently.

Questions to be addressed:

1) What is the relative proportion of subsalt halokinetic folding and simple truncations with no folding? Is there any correlation between the presence of folded strata and base-salt geometry (flats, shallow ramps, steep ramps)? Does the distribution depend on the size of the canopy or the position on the canopy (e.g., basinal or lateral edge)?
2) Similarly, what controls the development of subsalt thrusts? Are they found more often on large salt canopies with significant basinward translation of the overburden, are they better developed at the frontal or lateral edges, are they preferentially located at flat-ramp transitions, etc?
3) What is the internal character of subsalt rubble zones? Is there a single zone of disturbed strata or are there multiple zones that are interbedded with minibasin strata? Where there are closely spaced wells, is the rubble zone laterally continuous or highly variable? How common is it to not have any rubble zone at all?

4) Is there any correlation between presence and thickness of rubble zone and salt geometry? In other words, what is the influence of such factors as the size of the salt sheet, the position on the salt sheet, and the base-salt dip?
5) What role does the depositional environment play? Salt sheets in the GoM can have quite thick roofs, whereas those in South Australia most likely had thin or no roofs due to the shallow water depths and possible subaerial exposure of the sheet tops. If rubble zones represent, at least in part, slumped carapace (Kilby et al., 2008), then roof presence and thickness will be a critical variable.

Margin-Scale Component

Our field areas in northern Spain are located on what was a passive margin in the Early Cretaceous. Given the importance of passive-margin salt basins in petroleum exploration and production, we will use our work there as a springboard to examine several aspects of passive margins with salt. One is specific to the Pyrenees and the other is more general.

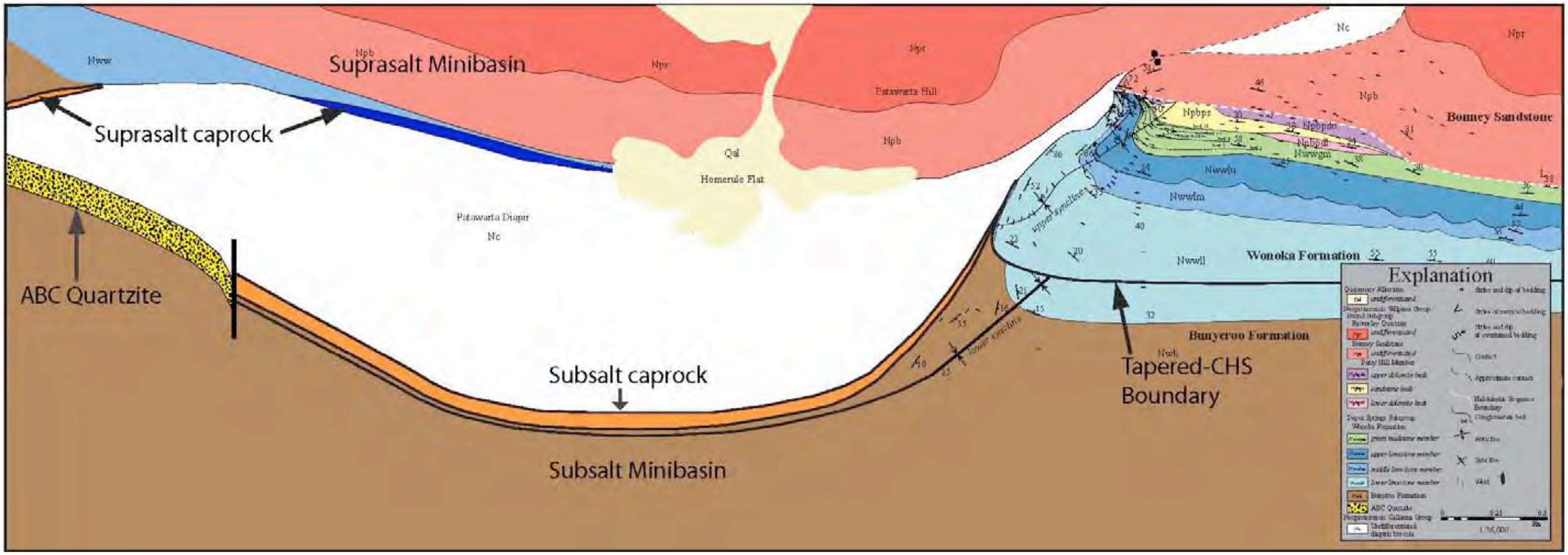


Figure 8. Geologic map of ramping Patawarta diapir, caprock and surrounding Neoproterozoic strata in both suprasalt and subsalt locations, Flinders Ranges, South Australia. Modified from Kernen at al. 2012.

Objective 1

Determine the influence of salt in the structural development of the northern Spanish margin and its later inversion during the Pyrenean Orogeny.

The Triassic Keuper salt is a prerift salt, with extension starting near the end of the Jurassic. It thus decoupled to some degree both the thick-skinned rifting and the later thick-skinned inversion. It also served as the detachment for thin-skinned gravitational failure as the margin was tilted toward the north due to differential thermal and loading subsidence. The Basque Pyrenees in particular offer a natural laboratory to investigate these processes because of the combination of surface outcrops, 2-D seismic data of reasonable quality, and scattered well data. One task that is central to our investigation is the construction and sequential restoration of a regional cross section from the foreland basin in the south to the offshore in the Bay of Biscay.

Questions to be addressed:

1) How did salt decouple the extensional deformation recorded in the cover rocks from that in the underlying basement?
2) What was the influence of relief on the base salt generated during extension on post-rift gravity gliding?
3) In what ways did the salt and both the thick-skinned and thin-skinned structures impact the style of Pyrenean shortening?
4) When and how were diapirs triggered and how were they subsequently modified during various deformational stages?

Objective 2

Apply modern concepts for hyperextended margins to improving our understanding of evaporite deposition and subsequent salt tectonics on passive margins.

In recent years, studies of the conjugate Iberian-Newfoundland margins and outcrops in the Alps have revolutionized our thinking on the development of non-volcanic hyperextended margins. Classic and competing models of McKenzie-style pure-shear extension and Wernicke-style simple-shear extension have been modified and combined into a four stage model (e.g., Lavier and Manatschal, 2007; Peron-Pinvidic and Manatschal, 2009): stretching, thinning, exhumation, and spreading. This model has critical implications for the origin and evolution of passive-margin salt basins.

Questions to be addressed:

1) What are the differences in areal and thickness distribution of evaporites between synrift salt, syn-stretching salt, syn-thinning salt, syn-exhumation salt, and syn-spreading salt? Are any stages more or less suitable for evaporite deposition?
2) Does deposition during different stages have any influence on evaporite chemisty and the relative proportions of various lithologies?
3) How do subsequent stages of extension modify the salt geometry and what influence does this have on post-salt deformation?
4) How are diapirs and salt movement triggered in the various settings and what is the dominant nature of subsequent salt tectonics?
5) Which salt basins along the various passive margins fit into each category? Is there any correlation between salt-basin type and hydrocarbon potential?

Significance

Findings from this research will have direct applicability to developing hydrocarbon exploration and production concepts in salt-related hydrocarbon systems elsewhere. Sedimentologic and structural data derived from exposures in the Paradox basin, Willouran and Flinders Ranges, and Spanish Pyrenees will be of fundamental importance in testing and calibrating existing salt-tectonic models derived from scaled laboratory and computer models or high resolution seismic and well log studies of subsurface salt bodies (including the ones to be carried out here), and in generating new models if existing ones are inadequate. Determining the patterns of near-diapir deformation will help in delineating the size and compartmentalization of diapir-flank fields. Better understanding of halokinetic growth-stratal geometries and facies distribution will provide important predictive tools for determining reservoir charge and quality and seal character in analogous fields. Regional correlation of both depositional sequences and halokinetic sequences will have important bearing on mechanisms of evaporite diapirism, and evaluating the relative rates of salt supply and sediment influx (plus or minus shortening or extension) acting on the system. Correlations between diapir-flank deformation and basin stratigraphy may help to constrain rates of diapirism, whether constant or episodic, and the mobility of allochthonous salt bodies. Studies of salt welds, the juxtaposed structural and stratigraphic relationships, and the evidence for and against fluid flow along or across welds, will help exploration companies better assess the likelihood of weld seal. Development of improved models of allochthonous salt emplacement and associated salt-sediment interaction will lead to better predictions and understanding of what might be encountered when a wells exits the base of a salt sheet. Finally, development of a modern classification scheme for passive-margin salt basins will aid in regional assessments of various aspects of the petroleum systems in these basins.

The three outcropping salt basins also provide unparalleled field areas for schools aimed at teaching petroleum geologists, geophysicists, and engineers the fundamental geometries of rising salt bodies and their interaction with coevally deposited sediments and to assist in visualization of geologic features they typically only view on seismic and well log data sets. The Paradox basin offers three-dimensional exposures of halokinetic sequence development on the flanks of large salt walls. The Spanish outcrops include diapirs in various depositional settings from subaerial to shallow water to deep water. The Flinders Ranges provide a wider variety of salt features and depositional facies, including numerous examples of allochthonous salt, and provides an important basis for comparison.

Deliverables

Each of the primary outcrop-based objectives will be addressed by the principal investigator (Kate Giles). Consultants, collaborators, and graduate students will work on specific aspects of these objectives and on the seismic and margin-scale objectives, with Dr. Giles organizing and coordinating their 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 at facilities either at the University of Texas-El Paso or in Moab, Utah. The meetings will generally have a day or day-and-a half of oral and poster presentations that summarize the results of our research. The oral presentations will be followed by time to address individual questions or specific aspects of our research. The meeting will be followed by a 2-3 day field trip to the Paradox basin outcrops to view the salt structures and highlight the new research datasets completed that year. The annual meeting will be held in the fall of each year for both logistical reasons and climatic reasons, but scheduled so as not to conflict with hunting season. Over the 5 year duration of this project we will hold at least one of the annual review meetings in Adelaide, Australia and provide a week-long field trip to the Flinders Ranges. That meeting will be held in June or July for logistical and climatic reasons.

The primary form of deliverables will be preprints of all manuscripts, abstracts for meetings, student theses, and annual meeting presentations compiled each year on a CD and accessible for downloading from our password protected website. In this way subscribers will have access to our results in advance of publication. However, there will be no restrictions placed by subscribers on our research in terms of content or timing of release to general public once it has been presented to the consortium. The annual field trip will include a guidebook and may serve as a salt tectonic field school for participants. We also envision this as an opportunity for intellectual exchange between industry and academia in regard to understanding the nature of these very complex systems and helping the research team adjust the project focus to address issues faced by the industry people. 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.

APPENDIX A
Geologic Setting of the Research Field Areas
Paradox Basin, Utah and Colorado

The asymmetric Paradox basin of eastern Utah and western Colorado developed in middle Pennsylvanian time adjacent to the NW-trending basement-cored Uncompahgre uplift (Figure 9a; Baker et al., 1933; Wengerd and Strickland, 1954; Elston et al., 1962). The Paradox Formation, a thick succession of cyclic Pennsylvanian shale, dolostone, halite and potassium salt minerals, defines the limits of the basin (Peterson and Hite, 1969; Hite et al., 1972; Condon, 1997). The Paradox Formation is overlain by Pennsylvanian and Permian siliciclastic strata that decrease in grain size and change facies to the southwest, creating a complex mosaic of facies and resulting complex stratigraphic nomenclature (Baars, 1961; Condon, 1997). Salt diapirism in the form of elongate salt walls took place during Pennsylvanian-Jurassic time, as indicated by thining and upturn of strata onto elongate salt walls (Shoemaker et al., 1958; Doelling, 1988; Trudgill et al., 2004; Trudgill, 2011).

The proximal basin fill constitutes the undifferentiated Cutler Group (Figure 9b, 10), a Pennsylvanian-Permian arkosic alluvial wedge approximately 5 km thick near the Uncompahgre uplift, which grades southwestward to a thick section of cyclic middle Pennsylvanian evaporite, shale and carbonate of the Paradox Formation into middle and late Pennsylvanian carbonates of the Paradox and Honaker Trail formations on the southwest flank of the basin (Barbeau, 2003). The strongly progradational Early Permian part of the alluvial wedge grades southwestward into marginal marine, eolian and fluvial siliciclastic and subordinate carbonate strata of the Cutler Group (Condon, 1997). The Lower Triassic Moenkopi Formation, which unconformably overlies the Cutler Group and was likewise derived from the Uncompahgre uplift, 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; Trudgill, 2011). The Upper Triassic Chinle Formation overlies the Moenkopi Formation. Salt withdrawal adjacent to the salt walls strongly influenced Chinle thickness and sediment dispersal fairways. The Cutler, Moenkopi, and Chinle formations contain diapir-derived detritus consisting of dolostone and gypsum clasts derived from salt wall layered caprock exposed both during the Permian and Triassic (Lawton and Buck, 2006; Trudgill, 2011; Shock, 2012).

Salt walls in the northeastern part of the basin trend 310º, parallel to the length of the basin (Figure 9). Where not covered by a thin veneer of Neogene surficial deposits, gypsum, black shale and dolostone of the Paradox Formation crop out locally on the flanks and rarely near the axial parts of eroded salt walls. Permian through Jurassic strata dip northeast and southwest away from the salt walls and thin toward the walls; dips are steep to overturned near salt walls and decrease away from the diapir over a distance of approximately 700m and upward through the section. Abrupt dip changes across bed boundaries in Cutler, Moenkopi, and Chinle beds indicate that unconformity-bounded halokinetic sequences are present in the section. Layered caprock has been identified Castle Valley and Moab valley (Fig. 9b; Shock, 2012). On the basis of isopach trends and sediment grain size, the arkosic wedge of the Cutler Formation has long been inferred to have prograded directly to the southwest, away from the Uncompahgre uplift (e.g., Wengerd and Matheny, 1958; Baars, 1961). This direction of sediment progradation requires that the dispersal systems routinely overtopped salt walls in their paths. Nevertheless, the salt walls strongly control the distribution of eolian and fluvial facies in intervening minibasins (Baars, 1961; Matthews et al., 2007), indicating the likelihood that the walls served at times as barriers to sediment dispersal.

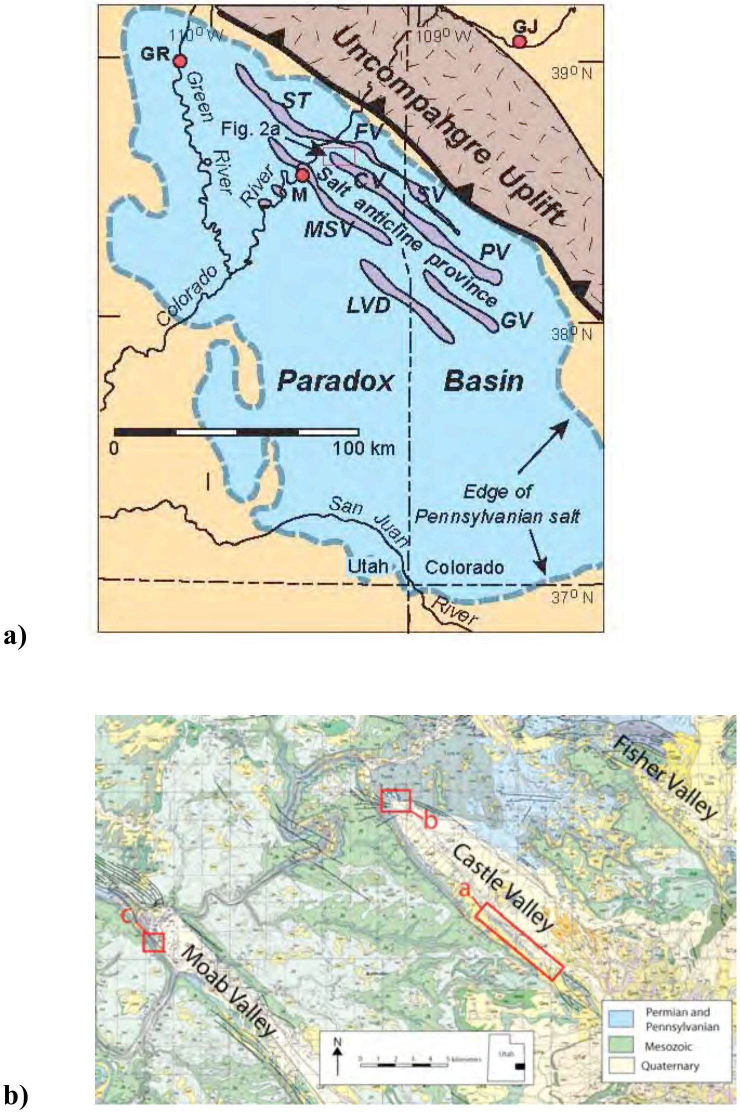
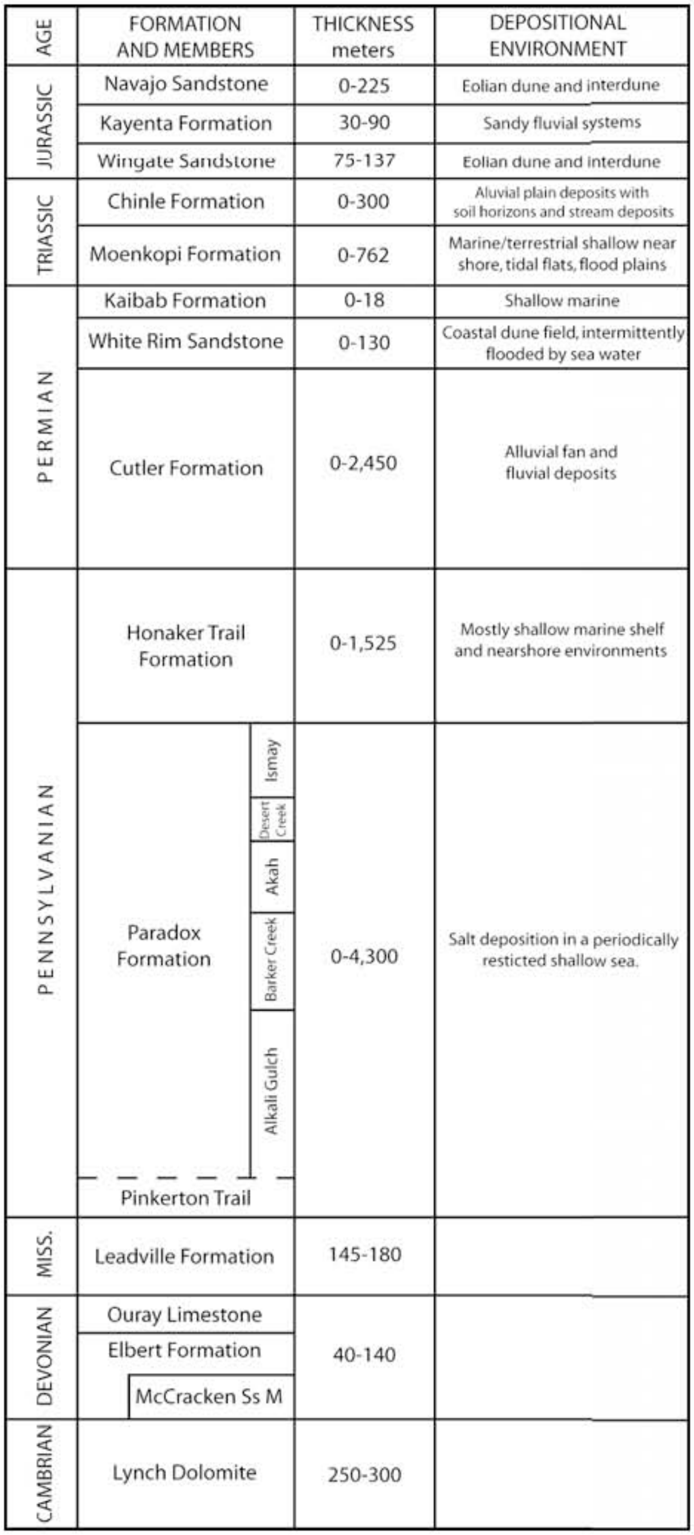


Figure 9. Maps of the Paradox basin in southeast Utah and southwest Colorado.

a) Map of salt wall anticlines in the Paradox basin. Red dots are cities: GR-Green River, M-Moab, GJ-Grand Junction. Purple polygons are salt-cored anticlines: ST-Salt Cache Valley, FV-Fisher Valley, SV-SinbadValley, CV-Castle Valley, PV-Paradox Valley, MSV-Moab Spanish Valley, GV-Gypsum Valley, LVD-Lisbon Valley. From Lawton and Buck (2006).

b) Geologic map of northwest end Castle Valley and Moab Valley field areas. A-outcrop area of Permian caprock, b-outcrop area of Triassic caprock, c-outcrop area of Jurassic caprock. Modified from Doelling (1988) and Shock (2012).



AGE	FORMATION AND MEMBERS	THICKNESS meters	DEPOSITIONAL ENVIRONMENT
JURASSIC	Navajo Sandstone	0-225	Eolian dune and interdune
	Kayenta Formation	30-90	Sandy fluvial systems
	Wingate Sandstone	75-137	Eolian dune and interdune
TRIASSIC	Chinle Formation	0-300	Aluvial plain deposits with soil horizons and stream deposits
	Moenkopi Formation	0-762	Marine/terrestrial shallow near shore, tidal flats, flood plains
PERMIAN	Kaibab Formation	0-18	Shallow marine
	White Rim Sandstone	0-130	Coastal dune field, intermittently flooded by sea water
	Cutler Formation	0-2,450	Alluvial fan and fluvial deposits
PENNSYLVANIAN	Honaker Trail Formation	0-1,525	Mostly shallow marine shelf and nearshore environments
	Paradox Formation Ismay Desert Creek Akah Barker Creek Alkali Gulch Pinkerton Trail	0-4,300	Salt deposition in a periodically resticted shallow sea.
MISS.	Leadville Formation	145-180	
DEVONIAN	Ouray Limestone Elbert Formation McCracken Ss M	40-140	
CAMBRIAN	Lynch Dolomite	250-300	

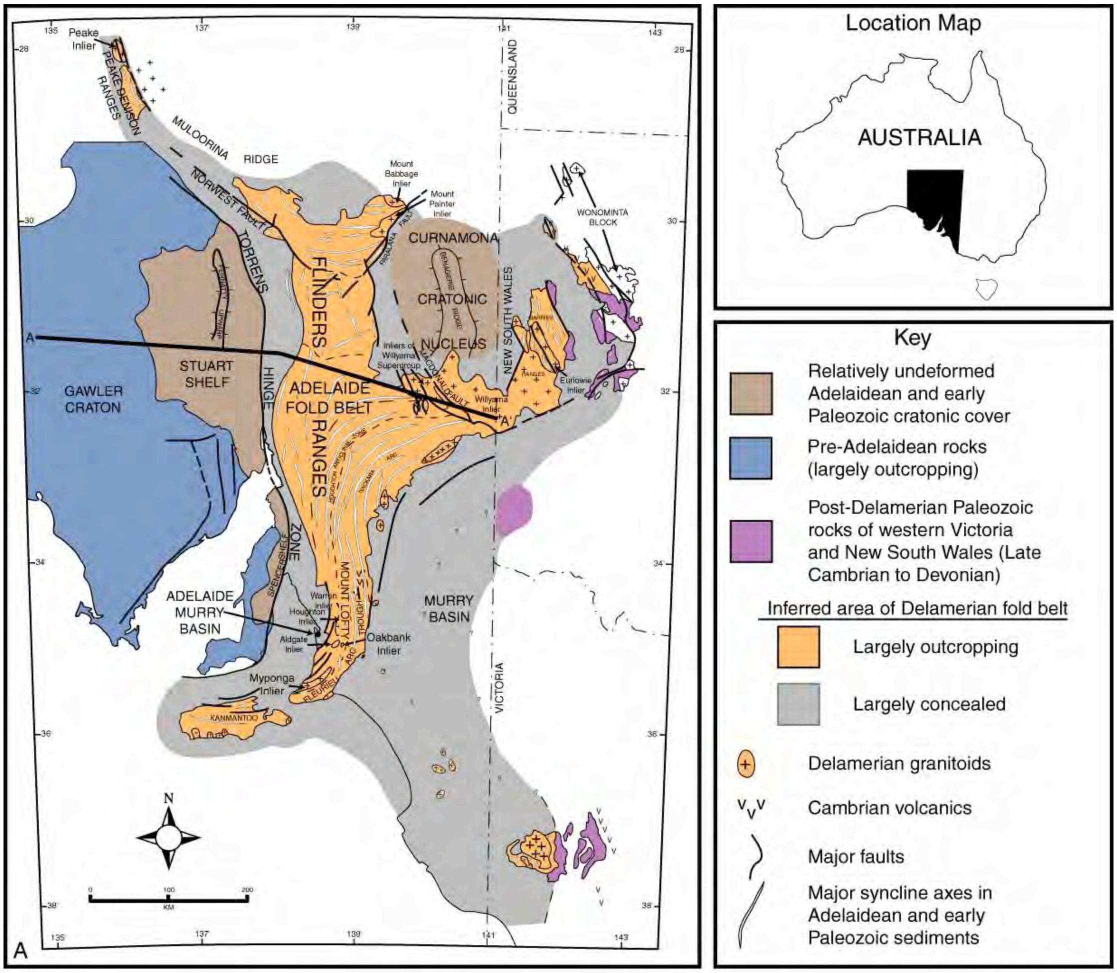
Figure 10. Stratigraphy of the Paradox Basin. Adapted from Trudgill et. al (2004).

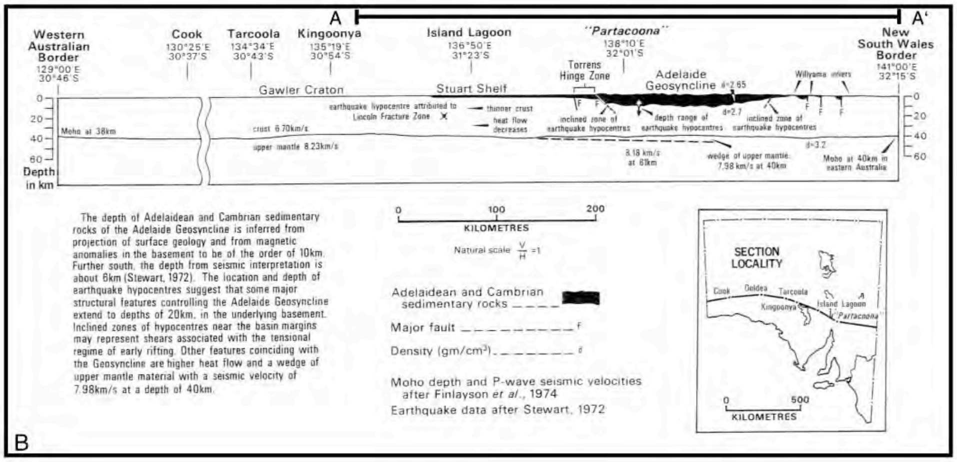
Flinders and Willouran Ranges, South Australia

The Flinders Ranges are part of a north-south trending mountain belt that lies to the north of Adelaide, in south central Australia (Figure 11). The Flinders Ranges, along with the Mount Lofty, Willouran, Peake and Denison ranges, expose strata of Precambrian through Cambrian age that were collectively referred to as the Adelaide geosyncline (Preiss, 1987) but are better termed the Adelaide fold belt (Jenkins, 1990; Marshak and Flöttmann, 1996). The highly deformed Adelaide fold belt is separated from the relatively undeformed Stuart Shelf and Gawler Craton to the west by the Torrens Hinge Zone, a zone of flexuring and faulting that marks a transition zone between the two areas (Figure 11). The eastern margin of the Adelaide fold belt is more obscure and is bounded by faults separating it from the Curnamona Cratonic Nucleus to the northeast and the Murray basin to the southeast. The Adelaide fold belt is currently thought to have initiated as a deeply subsiding basin between the Gawler and Curnamona cratonic landmasses in a rift or aulocogen tectonic setting (Sprigg, 1952; Scheiber, 1973; von der Borch, 1980; Preiss, 1983). It was subsequently deformed during the Late Cambrian-Ordovician Delamerian orogeny. The basin accumulated a very thick succession (as much as 20,000m) of marine to non-marine strata during the Neoproterozoic and Early Cambrian. The Willouran Callanna Group (Figure 12) represents the basal strata of the Adelaide Fold Belt succession and rests unconformably above Archean and Paleoproterozoic metamorphic and igneous basement rocks. The Callana Group includes a mixed assemblage of evaporites (non-marine), red beds, marginal marine carbonates and clastics, and alkaline volcanics (Rowlands et al., 1980). These depositionally intercalated lithologies of the Callana Group are present as entrained clast lithologies in breccias that delineate more than 100 diapirs in the Adelaide Foldbelt (Figure 13). These diapirs started growing immediately after evaporite deposition (e.g., Dyson, 2004; Hearon, 2008; Hannah, 2009) and persisted throughout the time recorded by the exposed strata. Diapirism was passive, as indicated by clasts of Callana Group lithologies found in mass transport complexes commonly associated with halokinetic sequence boundaries throughout the Adelaide Fold Belt succession. Allochthonous salt was extruded at two different times during the basin history (Dyson, 2004, 2005; Rowan and Vendeville, 2006), forming salt sheets and multi-level canopies that are partly welded (Hearon, 2008; Hannah, 2009). Both primary diapirs and allochthonous canopies strongly influenced the geometries of structures formed during the Delamerian Orogeny (Rowan and Vendeville, 2006).

Above the Callana, at the base of primary minibasins, is the Burra Group (Figure 12), consisting of Torrensian fluvial deposits overlain by a series of marine transgressive-regressive cycles. Most of the clastic sediments are thought to have been sourced from the Gawlor Craton to the west and formed massive eastward prograding deltaic complexes near the Torrens Hinge Zone (Preiss, 1987). These marginal marine deposits probably deepened towards the southeast out to open ocean facies in the Murray Basin area. The Burra Group was broadly warped during the Sturtian and locally highly eroded. As a result, a regional unconformity separates the Burra Group from the overlying Umberatana Group. The regionally extensive Umberatana Group comprises interbedded non-marine, marginal marine and deep marine, mixed carbonates and clastics. The contrast in distribution of the Burra and the Umberatana suggests they may be separated by the "break-up unconformity" (Preiss, 1987). Marginal marine deposits accumulated along the western and northeastern edges of the Adelaide Fold Belt, while basinal conditions were present in axial regions to the north and southeast. This trend continued throughout the Marinoan with deposition of the Wilpena Group. Cambrian strata of the Hawker Group unconformably overlie the Wilpena Group and primarily consist of regionally extensive marine limestone with local development of turbidites in minibasins.

Our primary focus will be on detailed structural and stratigraphic analysis of the following diapir systems (Fig. 13) in order to address the objectives and questions outlined in the proposal: Breaden Hill and Witchelina diapirs in the Willouran Range and Patawarta, Pinda, Wirrealpa, Loch Ness and Oladdie diapirs in the Flinders Ranges.





The depth of Adelaidean and Cambrian sedimentary rocks of the Adelaide Geosyncline is inferred from projection of surface geology and from magnetic anomalies in the basement to be of the order of 10km. Further south, the depth from seismic interpretation is about 6km (Stewart, 1972). The location and depth of earthquake hypocentres suggest that some major structural features controlling the Adelaide Geosyncline extend to depths of 20km. in the underlying basement. Inclined zones of hypocentres near the basin margins may represent shears associated with the tensional regime of early rifting. Other features coinciding with the Geosyncline are higher heat flow and a wedge of upper mantle material with a seismic velocity of 7.98km/s at a depth of 40km.

Adelaidean and Cambrian sedimentary rocks ▬

Major fault F

Density (gm/cm³) d

Moho depth and P-wave seismic velocities after Finlayson *et al*., 1974

Earthquake data after Stewart, 1972

Figure 11A. Major Neoproterozoic-Cambrian geologic elements of South Australia (provinces of western Victoria and New South Wales). Modified from Preiss (1987).

Figure 11B. Interpreted crustal cross-section across the Central Flinders Ranges of the Adelaide fold belt From Preiss (1987).

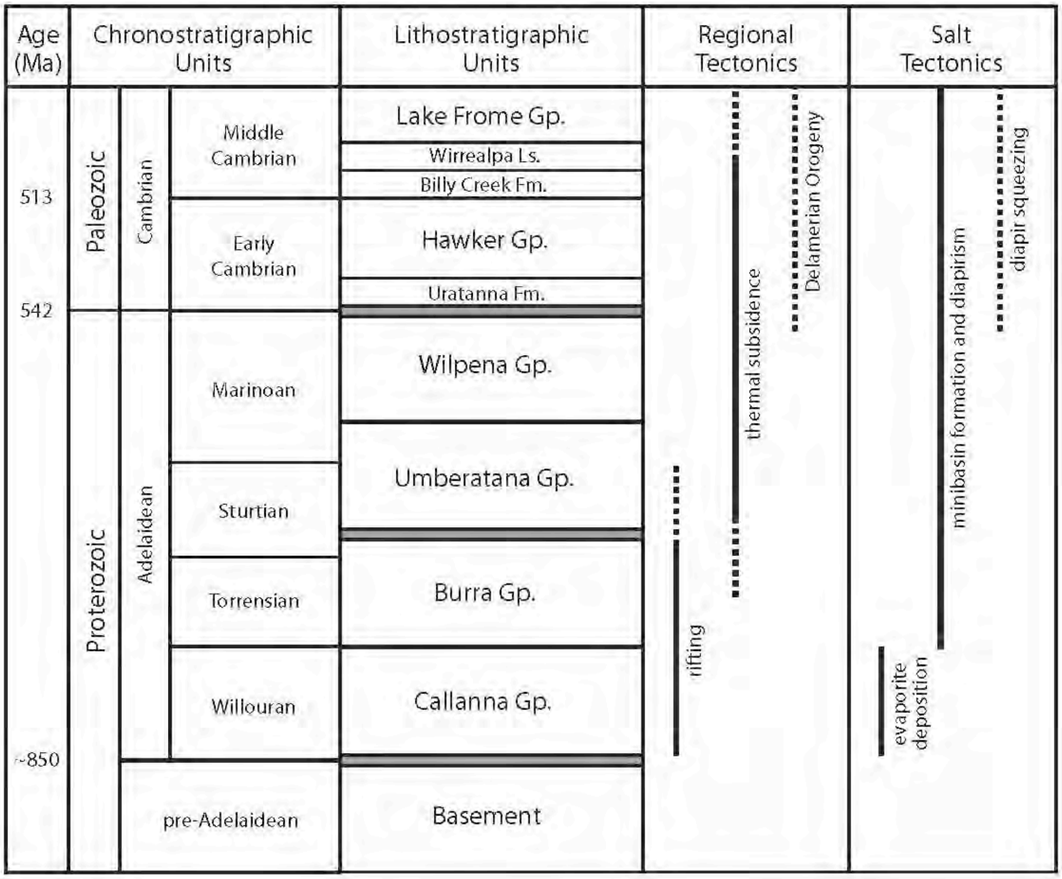


Figure 12. Neoproterozoic-Cambrian lithostratigraphy of the Flinders Ranges, South Australia. Adapted from Preiss (1987).

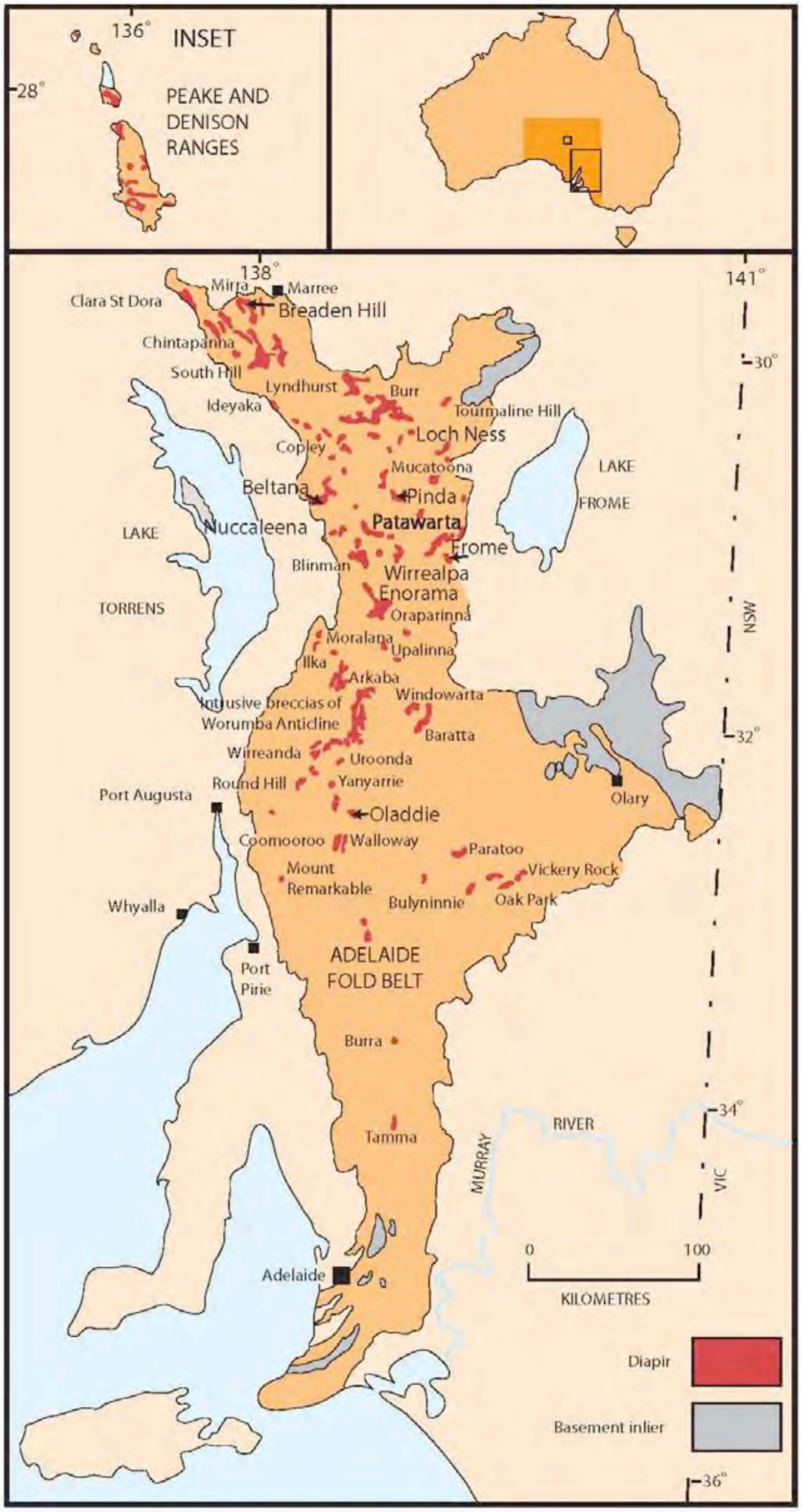


Figure 13. Map of Adelaide fold belt/Flinders Ranges area showing location of diapirs. Modified from Preiss (1987).

Basque Pyrenees, Northeast Spain

The Basque Pyrenees (Fig. 14) in the northern part of the Iberian Peninsula are part of an east-west trending mountain belt that extends from the Cantabrian Range in the west to the eastern end of the Pyrenees on the Mediterranean coast. The Pyrenees formed by inversion of a rift basin (in the east) to passive margin (in the west) that contained Triassic evaporites (e.g., Roest and Srivastava, 1991; Olivet, 1996). The salt basin was associated with the earlier rift breakup of Pangea in the Permo-Triassic. During the Triassic (Fig. 15), sabhka evaporites of the Muschelkalk and Keuper formations were deposited regionally across the Iberian and European plates. The evaporite sequences consist of halite, gypsum/anhydrite, potassium and magnesium salts, red and green shales, dolomitic marls, dolomites, and volcanics and shallow intrusives ("ophites"). Above the Keuper is a regionally extensive Jurassic carbonate platform. During the latest Jurassic (Tithonian) and much of the Early Cretaceous, a second phase of extension related to the opening of the North Atlantic and counter-clockwise rotation of Iberia away from the Armorican Massif led to mantle exhumation and oceanic spreading beginning in the Albian (e.g., Gong et al, 2008; Jammes et al., 2009). Rift sediments comprise alluvial, fluvial and deltaic siliciclastics that progressively deepened into turbidite successions to the north. From the Late Cretaceous to Early Miocene, continental collision between the Iberian and European plates resulted in inversion of the rift basin/margin and southward thrust displacement (Muñoz et al., 1986; Muñoz et al., 1992) to form the Pyrenean orogenic belt.

The Keuper evaporites served to decouple the early extension and also served as a detachment during post-rift gravity gliding and the later shortening. In addition, there are more than 20 diapirs throughout the Basque-Cantabrian salt basin (Fig. 16). Most were probably triggered during the extension and influenced Cretaceous sediment dispersal. Our field studies will initially focus on the Bakio diapir but will expand to other appropriate locales. The Bakio diapir is well-exposed in sea cliffs along the northern coast of Spain (Fig. 17) and forms a northeast-southwest trending salt wall that extends for several kilometers offshore into the Bay of Biscay. The diapir is composed of Keuper evaporites and is surrounded by outcrops of Aptian and Albian carbonate and siliciclastic turbidites and MTC's that are deformed into halokinetic sequences along the margin of the diapir (Fig. 18). These outcrops provide a rare opportunity to observe the interaction of salt diapirism and deepwater gravity flows.

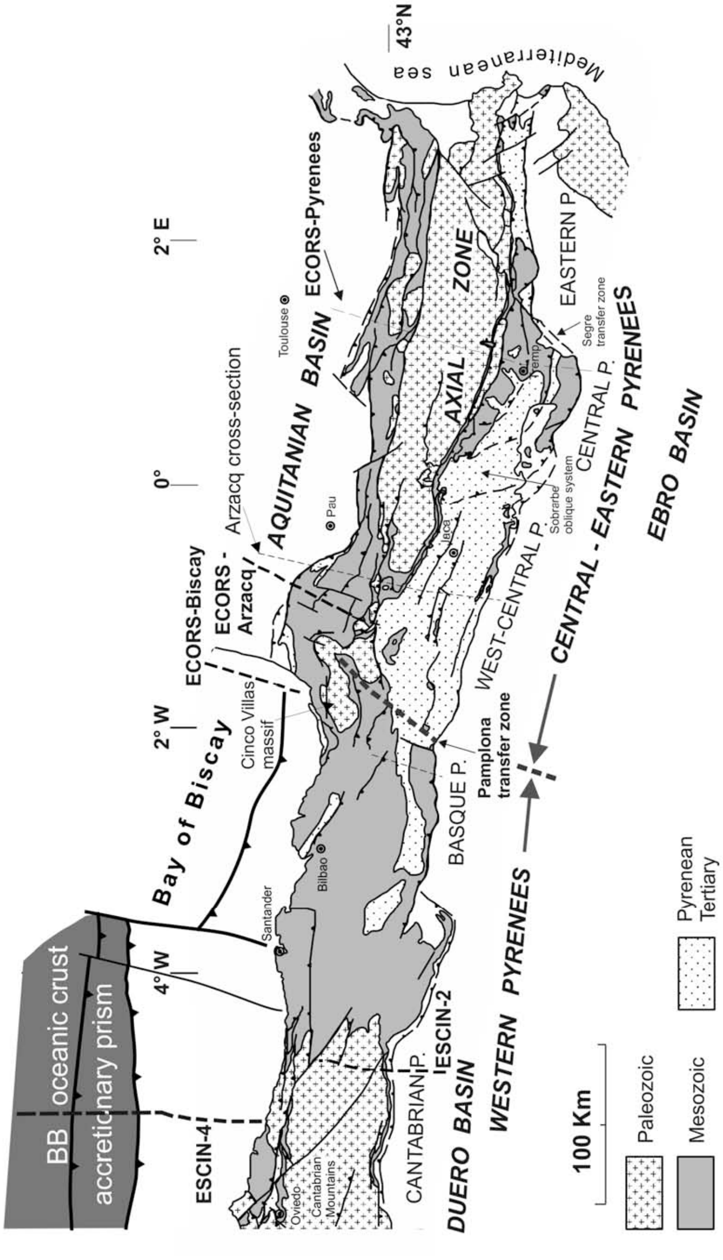


Figure 14. Map of structural and tectonic elements of the Basque Pyrenees.

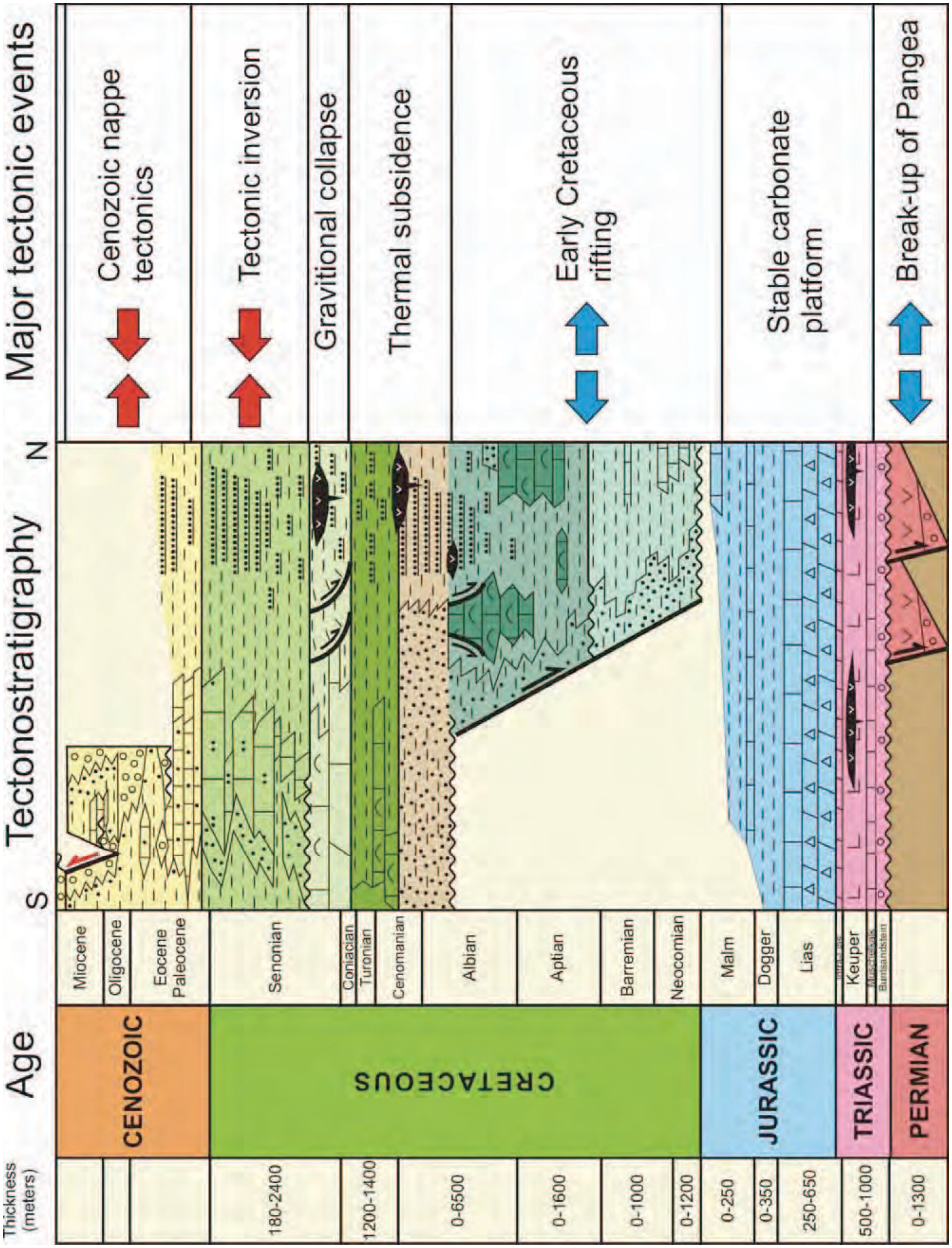


Figure 15. Chronostratigraphic diagram of the Basque Pyrenees showing the main tectonic events that affected the Basque-Cantabrian Mesozoic basin.

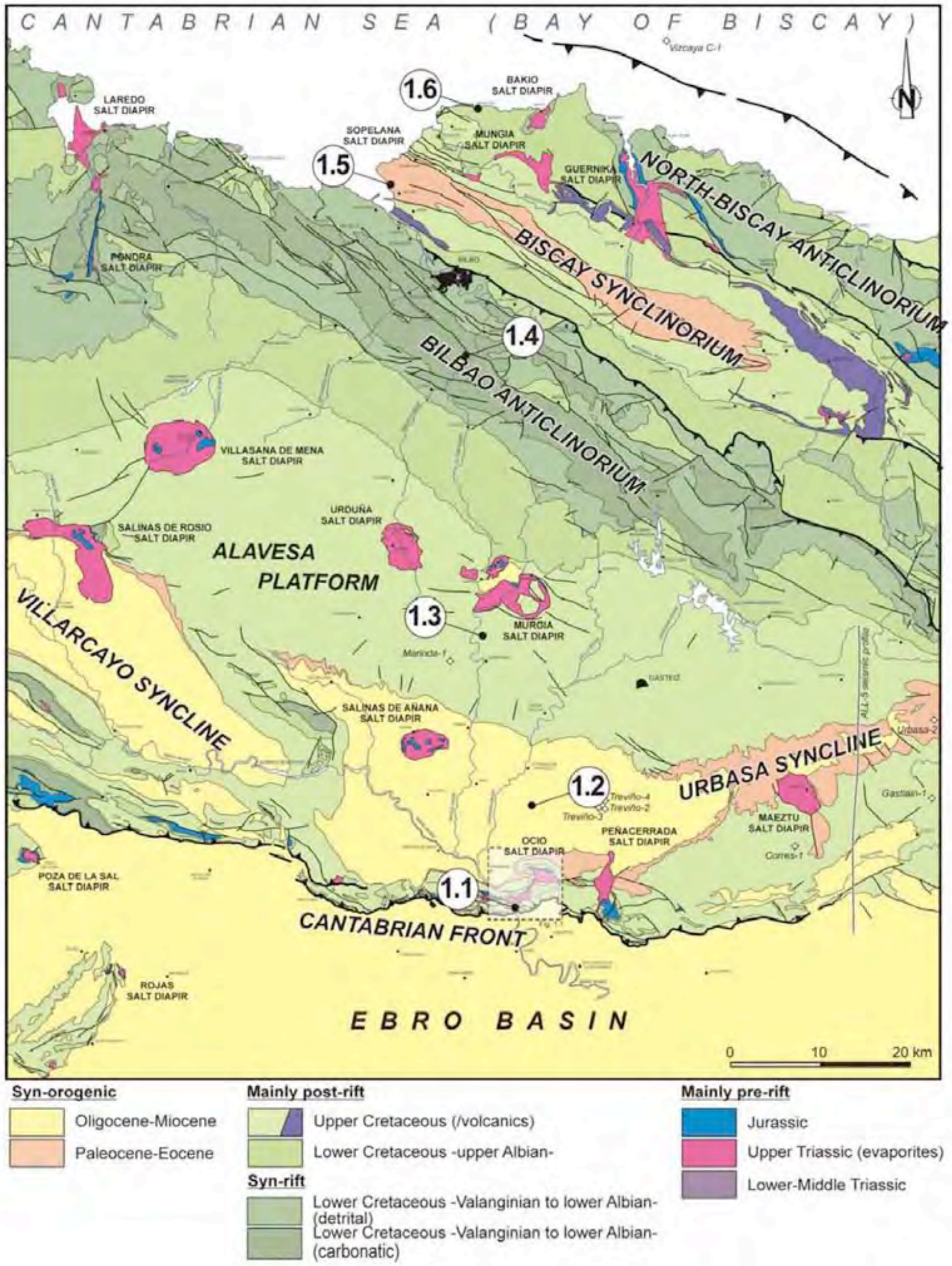


Figure 16. Geologic map of Basque Pyrenees showing the location of salt diapirs.

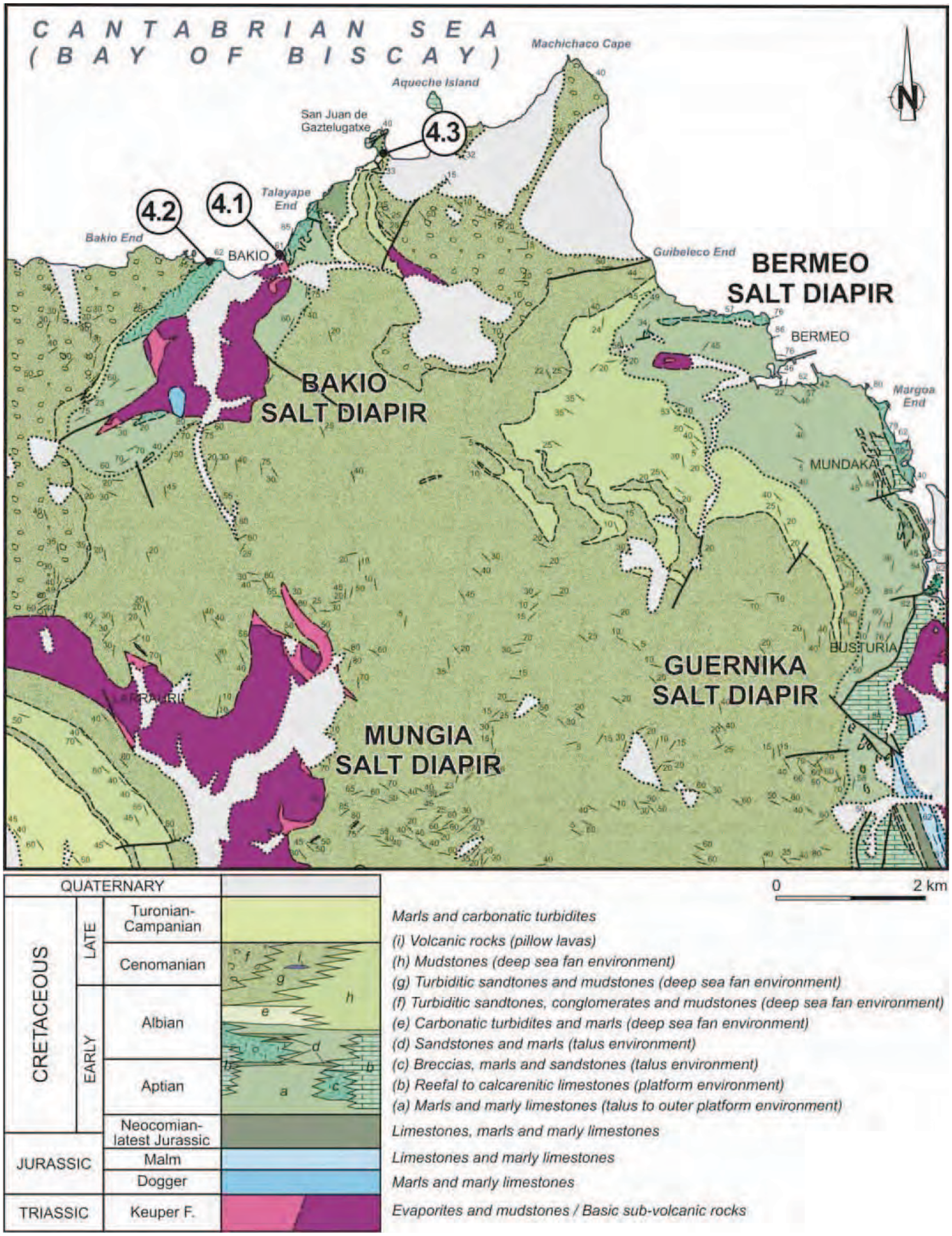


Figure 17. Geological map of the Bakio, Mungia and Guernika diapirs.

Figure 18 Panoramic view of the western cliffs of Bakio showing the main structural and stratigraphical features of the Aptian to middle Albian halokinetic sequences developed at the western flank of the Bakio Salt Diapir (looking to the Southwest from the sea). The western wall of this diapir is located just off the left-hand margin of the photograph.

APPENDIX B

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Wengerd, S.A., and Strickland, J.W., 1954, Pennsylvanian stratigraphy of Paradox basin, Four Corners region, Colorado and Utah: American Association of Petroleum Geologists Bulletin, v. 38, p. 2157-2199.

Whipple, K.X., 2009, The influence of climate on the tectonic evolution of mountain belts, Nature Geoscience, v. 2, p. 97-104.

Yeilding, C.A., and Travis, C.J., 1997, Nature and significance of irregular geometries at the salt-sediment interface: American Association of Petroleum Geologists Annual Meeting Abstracts, p. 156.

APPENDIX C

RESEARCH PERSONNEL

Principal Investigator: Katherine A. Giles (The University of Texas at El Paso) – sedimentology and sequence stratigraphy

Collaborator: Richard Langford (The University of Texas at El Paso) – sedimentology and sequence stratigraphy

Consultant: Mark Rowan (Rowan Consulting, Inc.) – structure, tectonics, and seismic interpretation

Collaborator: Mark Fischer (Northern Illinois University) – structure, fluid flow

Collaborator: Thomas Hearon, IV (Colorado School of Mines) – structure, tectonics, and stratigraphy,

Collaborator: Josep Anton Muñoz (University of Barcelona) – structure, tectonics

Collaborator: Eduard Roca (University of Barcelona) – structure, tectonics

Collaborator: J. Carl Fiduk (WesternGeco) – structure, stratigraphy, seismic interpretation

The Principal Investigator, consultants, and collaborators form a highly qualified team that brings different and complementary skills to the project. All the researchers have held industry positions in the past and have industry consulting experience. Giles' expertise is in carbonate sedimentology and petrology, sequence stratigraphy and their application to regional tectonics. Langford is a clastic sedimentologist with expertise in eolian systems and tectonic geomorphology. Rowan is an expert in salt tectonics and its application to the Gulf of Mexico and other salt basins worldwide. Lawton is a stratigrapher and clastic sedimentologist with experience in growth strata and progressive unconformities. Fischer is a structural geologist with industry experience and utilizes C, O, and S isotopes in fracture and vein-filling cements to understand the timing and environment of fluid migration and structure development. Hearon is a structural geologist with emphasis on salt tectonics. Muñoz and Roca are both professors in structural geology and tectonics. Fiduk is an expert on salt tectonics in the Gulf of Mexico, Brazil, and other salt basins. The following pages include brief vitae for the Principal Investigator, collaborators and consultants.

In addition, we will be supporting graduate students (both Ph.D. and Master's), Post-doctoral researchers, and undergraduate majors from UTEP and consortium affiliated universities that will be working on the project. The exact number will depend on the availability of qualified students and the level of funding that we receive. We envision 15-20 graduate students, 5 postdocs, and 5-10 undergraduate majors working on the project during the 5-year duration of research project.

KATHERINE A. GILES

Lloyd A. Nelson Professorship, Department of Geological Sciences
Director, Institute of Tectonic Studies
The University of Texas at El Paso, El Paso, TX, 79968-0555
(915)747-7075; kagiles@utep.edu

EDUCATION

1991 - Ph.D. in Geology, University of Arizona, Tucson
Dissertation Title: Interpretation of the lower Mississippian Joana Limestone and implications for the Antler orogenic system.
Advisor: William R. Dickinson

1985 - M.S. in Geology, University of Iowa, Iowa City
Thesis Title: Stratigraphy, petrology, and interpretation of the Iatan Limestone (Upper Pennsylvanian) in northwestern Missouri and adjacent states.
Advisor: Philip H. Heckel

1981 - B.S. in Geology, University of Wisconsin, Madison

PROFESSIONAL EXPERIENCE – Post-Graduate only

2012 - present: Lloyd A. Nelson Professor, Geological Sciences, University of Texas at El Paso

1993-2011: Professor, Geological Sciences, New Mexico State University

1998-2011: Director, Institute of Tectonic Studies, New Mexico State University.
Co-PI, Salt-Sediment Interaction Joint Industry Research Consortium, Phases I- IV

1998-present: Consulting Geologist, Reservoir characterization and continuity, stratigraphic analysis, salt tectonics

1991-1993: Senior Carbonate Research Geologist, Exxon Production Research Company, Houston, TX

RECENT AWARDS AND HONORS

AAPG Shelton Search and Discovery Award, 2011
NMSU University Research Council Distinguished Career Award, 2009
American Association Petroleum Geologists Distinguished Lecturer 2007-2008; AAPG DL Committee Member (2009-present) and Co-chair (2012 – 2014).
New Mexico Geological Society Honorary Member 2004; President 2000; Executive Committee 1997-03.
Geological Society of America Fellow 2004.
Fulbright Scholar 2000-2001, Science and Technology Division.
American Chemical Society-Petroleum Research Fund Advisory Board, 2004-2010
Institute of Tectonic Studies, NMSU, Appointed Director 1999-2011.
SEPM Carbonate Research Group Appointed Chair 2000-2004.

SELECTED PROPOSAL RELATED PUBLICATIONS (* denotes student advisees of K. A. Giles)

*Andrie, J.R.**, Giles, K.A.,** Lawton, T.F., Rowan, M.G., 2012, Halokinetic-sequence stratigraphy, fluvial sedimentology, and structural geometry of the Eocene Carroza Formation along La Popa salt weld, La Popa Basin, Mexico; *in* Alsop, G. I., et al.(eds), Salt Tectonics, Sediments and Prospectivity; Geological Society of London Special Publications, 363, p. 59-79.

Giles, K. A. and Rowan, M. G., 2012, Concepts in halokinetic–sequence deformation and stratigraphy; *in* Alsop, G. I., et al. (eds), Salt Tectonics, Sediments and Prospectivity; Geological Society of London Special Publications, 363, p. 7-31.

*Kernen, R.A., **Giles, K.A.,** Rowan, M.G., Lawton, T. F., and Hearon, T.E., IV**.** , 2012. Depositional and halokinetic-sequence stratigraphy of the Neoproterozoic Wonoka Formation adjacent to Patawarta allochthonous salt sheet, Central Flinders Ranges, South Australia; *in* Alsop, G. I., et al. (eds), Salt Tectonics, Sediments and Prospectivity; Geological Society of London Special Publications, 363, p. 81-105.

Rowan, M.G., Lawton, T.F., and **Giles, K.A.** , 2012, Anatomy of an exposed vertical salt weld and flanking strata La Popa Basin, Mexico. *in* Alsop, G. I., et al. (eds), Salt Tectonics, Sediments and Prospectivity; Geological Society of London Special Publications, 363, p. 33-57.

Catuneanu, O., Abreu, V., Bhatacharya, J. P., Blum, M. D., **Giles, K. A.,** and 23 others, 2009, Towards the standardization of sequence stratigraphy: Earth-Science Reviews, v. 92, p. 1-33.

Giles, K. A, *Druke, D. C., *Mercer, D. W., and *Hunnicutt-Mack, L., 2008, Controls on Upper Cretaceous (Maastrichtian) Heterozoan Carbonate Platforms Developed on Salt Diapirs, La Popa Basin, NE Mexico; *in*: Lukasik, J. and Simo, J. A, eds., Controls on Carbonate Platform Development, SEPM Special Pub. No. 89, p. 107 - 124.

*Aschoff, J. L. and **Giles, K. A.,** 2005, Salt diapir-influenced, shallow-marine sediment dispersal patterns: Insights from outcrop analogs: American Association of Petroleum Geologists Bulletin, v. 89, p. 447-469.

Lawton, T. F., *Shipley, K. W., *Aschoff, J. L., **Giles, K. A.,** and Vega, F. J., 2005, Basinward transport of Chicxulub ejecta by tsunami-induced backflow, La Popa basin, northeastern Mexico, and its implications for distribution of impact-related deposits flanking the Gulf of Mexico: Geology, v. 33, p. 81-84.

Giles, K. A., Lawton, T. F., and Rowan, M. G., 2004, Summary of Halokinetic Sequence Characteristics from Outcrop Studies of the La Popa Salt Basin, NE Mexico: *in* Post, P., et al. eds., Salt-Sediment Interaction and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century; 24th Annual GCS-SEPM Foundation Bob F. Perkins Research Conference Proceedings, p. 625-634.

Rowan, M. G., Lawton, T. F., **Giles, K. A.,** and Ratliff, R. A., 2003, Near-salt deformation in La Popa basin, Mexico, and the Northern Gulf of Mexico: A general model for passive diapirism: American Association of Petroleum Geologists Bulletin, v. 87, p. 733-756.

Giles, K. A. and Lawton, T. F., 2002, Halokinetic sequence stratigraphy adjacent to El Papalote diapir, La Popa basin, northeastern Mexico: American Association of Petroleum Geologist Bulletin, v. 86, p. 823-841.

Lawton, T. F., Vega, F. J., **Giles, K. A.,** and Rosales-Dominguez, C., 2001, Stratigraphy and origin of the La Popa basin, Nuevo Leon and Coahuila, Mexico, *in* Bartolini, C., Buffler, R. T., and Cantú-Chapa, A., eds., Mesozoic and Cenozoic evolution of the western Gulf of Mexico basin: Tectonics, sedimentary basins and petroleum systems: Tulsa, Oklahoma, American Association of Petroleum Geologists Memoir 75, p. 219-240.

Giles, K. A. and Lawton, T. F., 1999, Attributes and Evolution of an Exhumed Salt Weld, La Popa Basin, Northeastern Mexico: Geology, v. 27, p.323-326.

Dr. Richard P. Langford
Department of Geological Sciences
Professor
The University of Texas at El Paso, El Paso, TX, 79968-0555
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Education

Ph D, University of Utah, 1988.
  Major: Geology
  Dissertation Title: Modern and ancient fluvial-eolian interactions
MA, Indiana University, 1982.
  Major: Geology
  Dissertation Title: Depositional systems and geologic history of the lower part of the Fountain Formation, Manitou Embayment, Colorado
BA, Colorado College, 1979.
  Major: Geology, mineralogy, petrology, structural geology

Professional Positions

Professor, The University of Texas at El Paso. (September 1, 2008 - Present).
Associate Professor, The University of Texas at El Paso. (September 2002 - September 2008).
Asst. Professor, Sept. 1996 to Sept 2002 -- The University of Texas at El Paso.
Temporary Asst. Professor, Sept. 1995 to July 1996 -- Rutgers University. Teaching Introductory Geology courses and undergraduate Hydrology and Geophysics.
Research Associate, Bureau of Economic Geology, University of Texas, Austin, TX.
(January 1989 –April 1994)

Licensures and Certifications

Professional Geologist, Texas Board of Professional Geoscientists. (2001 - Present).

Professional Memberships

American Association of Petroleum Geologists, American Geophysical Union, Geological Society of America, International Association of Sedimentologists, SEPM Society for Sedimentary Geology.

Awards and Honors

Jack Bristol Award for Teaching, Phi Sigma Phi, Sigma Xi, Fellow Geological Society of America

Selected Peer Reviewed Articles

Langford, R. P., Pavlis, T. L., Budhathoki, P. 2011 Interactions Between Rift Tectonism and Sedimentation, Cretaceous Chihuahua Trough. American Association of Petroleum Geologists, Search and Discovery, 52. www.searchanddiscovery.net/documents/2010/50338langford/ndx_langford.pdf

Benker, C. S., Langford, R. P., Pavlis, T. L. (2011). Positional accuracy of the Google Earth terrain model derived from stratigraphic unconformities in the Big Bend region, Texas, USA. Geocarto International v. 26, 291-303.

Pavlis, T. L., Langford, R. P., Hurtado, J. M., Serpa, L. F. (2010) Computer based data acquisition and visualization systems in field geology: Results from 12 years of experimentation and future potential Geosphere.

Langford, R. P., Rose, J., Diane, W. (2009). Groundwater salinity as a control on development of eolian landscape: An example from the White Sands of New Mexico Geomorphology.

Geomorphology, 105(1-2), 39-49.

Langford, R. P., Pearson, K. M., Duncan, K. D., Tatum, D., Adams, L., Depret, P. (2007). Eolian Topography as a Control on Deposition, With Lessons From Modern Dune Seas: Permian Cedar Mesa Sandstone, SE Utah. *Journal of Sedimentary Research, 78*, 410-422.

Langford, R. P., and Chan, M. A., 1993, Downwind changes within an ancient dune sea, Permian Cedar Mesa Sandstone, southeast Utah: in, Modern and Ancient Eolian Depositional Environments. International Association of Sedimentologists Special Publication No. 16, p. 109-126.

Chan, M. A., Hunter, R. E., Loope, D. B., and Langford, R. P., 1992, Reflections on eolian and erg-margin systems. Journal of Sedimentary Petrology, v. 62, p. 917.

Collaborators & Other Affiliations

Collaborators
  Suresh Pillai (Texas A&M at College Station)
  Elizabeth Walsh (Univ. of Texas at El Paso)
Marjorie Chan, University of Utah
Dale Gillette, NOAA

Advisors. Lee J. Suttner, Indiana University; Marjorie Chan, University of Utah

Advisees: Adams, Luqman is in a postdoctoral position Prairie View A and M University. Emile Couroux(B.S., 1998; M.S., 2001) Sr. Geologist, Raba Kistner Inc. Marta Clepper is completing a Geology Ph.D. at the University of Kentucky, Crocker, Lynnette (B.S., 2005) Lynette is working for TriHydro Corporation in Anaheim, CA Duncan, Katy; M.S., 2006; Full time Geologist El Paso Corporation E&P and will reside in Denver Colorado. Kennedy, John Kennedy (PhD, 2004) email; 3/06, John works full time at WSMR (Caelum-Unitec), Brandi Poole Sellepack is an Exploration Geologist, Conoco Inc., Houston, TX., Krystal Pearson, Exploration Geologist for Chevron USA, Jessica Rose is an Exploration Geologist for Anadarko Petroleum, Houston, TX, Seeley, John M.; PhD, 1997 Taught as an assistant professor at Midwestern State University and now has taken a position as Regional Exploration Geologist with Uranium Resources, Inc. in Corpus Christi, Texas., David Sheba 2006 works as an exploration Geologist for Chevron USA in Midland Texas. Xie, Hongjie (PhD, 2002), 11/04 is an Assistant Professor in the Department of Earth and Environmental Sciences at UT San Antonio. Abdel-Fattah, Ahmad is working as a faculty member in Jordan

Service

Geological Society of America – Chair, Sedimentary Geology Division

Reviewer, American Association for the Advancement of Science, Washington DC. (January 10, 2010 - January 30, 2010). Numerous Journals

Board Member, Fort Bliss Restoration Advisory Board, El Paso, Texas. (March 1, 2009 - Present).

MARK G. ROWAN
Curriculum Vitae

SUMMARY

Internationally-renowned structural geologist with 30 years experience in petroleum exploration, structural consulting, industry training, and academic research and teaching. Primary expertise in salt tectonics, fold-and-thrust belts, rift basins, and inversion tectonics in settings around the world, with emphasis on determining three-dimensional geometry and evolution of complex structures using 3-D seismic interpretation, field investigations, and structural analysis. Over 70 published papers and 150 published abstracts. Regular instructor for AAPG short course on “Practical Salt Tectonics”. AAPG Distinguished Lecturer in 2005-2006, and AAPG International Distinguished Instructor for 2009-2010.

EDUCATION

California Institute of Technology 1971-1976
B.S. with Honors, Biology (1976)

University of Utah 1976-1979
part-time studies, Geology

University of California, Berkeley 1979-1982
M.S., Geology (1982)

University of Colorado, Boulder 1986-1991
Ph.D., Structural Geology (1991)

POSITIONS HELD

Exploration Geologist 1982-1985
Sohio Petroleum Co., Denver, Colorado

Associate Geologist, Senior Geologist 1985-1989
Geo-Logic Systems, Inc., Boulder, Colorado

Teaching and Research Assistant, 1986-1989
University of Colorado, Boulder

Consulting Geologist, Technical Director (1992) 1989-1992
Alastair Beach Associates, Glasgow, Scotland

Research Associate, Assistant Professor Adjunct (1994) 1992-1996
Dept. of Geological Sciences, Univ. of Colorado

Research Assistant Professor, Dept. of Geological Sciences, Univ. of Colorado 1996-1998
Research Fellow, Energy & Minerals Applied Research Center

President, Rowan Consulting, Inc., Boulder, CO 1998-

SELECTED PUBLICATIONS

1995 M.G. Rowan, Structural styles and evolution of allochthonous salt, central Louisiana outer shelf and upper slope, in Jackson, M.P.A., Roberts, D.G., & Snelson, S., eds., Salt Tectonics: A Global Perspective: AAPG Mem. 65, 199-228.

1997 M.G. Rowan, Three-dimensional geometry and evolution of a segmented detachment fold, Mississippi Fan foldbelt, Gulf of Mexico: J. Struct. Geol. 19, 463-480.

1998 M.G. Rowan & P. Weimer, Salt-sediment interaction, northern Green Canyon and Ewing Bank (offshore Louisiana), northern Gulf of Mexico: AAPG Bull. 82, 1055-1082.

1998 B.C. McBride, M.G. Rowan, & P. Weimer, The evolution of allochthonous salt systems, northern Green Canyon and Ewing Bank (offshore Louisiana), northern Gulf of Mexico: AAPG Bull. 82, 1013-1036.

1998 M.G. Rowan, B.S. Hart, S. Nelson, P. Flemings, & B.D. Trudgill, Three-dimensional geometry and evolution of a salt-related growth-fault array: EI-330 Field, offshore Louisiana, Gulf of Mexico: Marine and Petroleum Geology 15, 309-328.

1999 B.D. Trudgill, M.G. Rowan, J.C. Fiduk, P. Weimer, P.E. Gale, B.E. Korn, R.L. Phair, W.T. Gafford, G.R. Roberts, & S.W. Dobbs, The Perdido fold belt, northwestern deep Gulf of Mexico, Part 1: Structural geometry, evolution and regional implications: AAPG Bull. 83, 88-113.

1999 M.G. Rowan, M.P.A. Jackson, & B.D. Trudgill, Salt-related fault families and fault welds in the northern Gulf of Mexico: AAPG Bulletin 83, 1454-1484.

2000 M.G. Rowan, B.D. Trudgill, & J.C. Fiduk, Deep-water, salt-cored foldbelts: lessons from the Mississippi Fan and Perdido foldbelts, northern Gulf of Mexico, in Mohriak, W., & Talwani, M., eds., Atlantic Rifts and Continental Margins: American Geophysical Union Geophysical Monograph 115, 173-191.

2001 M.G. Rowan, R.A. Ratliff, B.D. Trudgill, & J. Barceló-Duarte, Emplacement and evolution of the Mahogany salt body, central Louisiana outer shelf, northern Gulf of Mexico: AAPG Bulletin 85, 947-969.

2003 M.G. Rowan, T.F. Lawton, K.A. Giles, & R.A. Ratliff, Near-diapir deformation in La Popa basin, Mexico, and the northern Gulf of Mexico: a general model for passive diapirism: AAPG Bulletin 87, 733-756.

2004 M.G. Rowan, F.J. Peel, & B.C. Vendeville, Gravity-driven foldbelts on passive margins, in K.R. McClay, ed., Thrust Belts and Petroleum Systems: AAPG Memoir 82, 157-182.

2004 M.G. Rowan, Do salt welds seal?, in P. Post et al., ed., Salt-Sediment Interactions and Hydrocarbon Prospectivity: GCSSEPM Research Conference Proceedings CD ROM.

2006 M.G. Rowan & B.C. Vendeville, Foldbelts with early salt withdrawal and diapirism: physical model and examples from the northern Gulf of Mexico and the Flinders Ranges, Australia: Marine and Petroleum Geology 23, 871-891.

2006 M.G. Rowan, compiler, Getting Started in Salt Tectonics: a Compendium of Influential Papers: AAPG/Datapages Getting Started Series No. 6, CD ROM.

2011 M.G. Rowan & K.F. Inman, Salt-related deformation recorded by allochthonous salt rather than growth strata: Gulf Coast Assoc. Geol. Soc. Transactions, v. 61, 379-390.

2012 M.G. Rowan & R.A. Ratliff, Cross-section restoration of salt-involved deformation: best practices and potential pitfalls, in R. Groshong, A. Gibbs, R.A. Ratliff, C. Bond, & D. Wiltschko (eds.), Chamberlin Centennial: A Critical Assessment of Balance and Restoration Technique and Interpretation: J. Structural Geology (online).

2012 J.C. Fiduk & M.G. Rowan, Analysis of folding and deformation within layered evaporites in Blocks BM-S-8 & -9, Santos Basin, Brazil, in I.A. Alsop, S.G. Archer, A.J. Hartley, N.T. Grant, & R. Hodgkinson (eds.), Salt Tectonics, Sediments and Prospectivity: Geol. Soc. London Spec. Pub. 363, p. 471-487.

2012 M.G. Rowan, T.F. Lawton, & K.A. Giles, Anatomy of an exposed vertical salt weld and flanking strata, La Popa Basin, Mexico, in I.A. Alsop, S.G. Archer, A.J. Hartley, N.T. Grant, & R. Hodgkinson (eds.), Salt Tectonics, Sediments and Prospectivity: Geol. Soc. London Spec. Pub. 363, p. 33-57.

2012 K.A. Giles & M.G. Rowan, Concepts in halokinetic-sequence deformation and stratigraphy, in I.A. Alsop, S.G. Archer, A.J. Hartley, N.T. Grant, & R. Hodgkinson (eds.), Salt Tectonics, Sediments and Prospectivity: Geol. Soc. London Spec. Pub. 363, p. 7-31.

THOMAS E. HEARON, IV
+1.575.644.7953
thomashearon@gmail.com

My research focus involves field-based characterization and structural and stratigraphic analysis of passive salt diapirs, allochthonous salt bodies and associated flanking halokinetic stratigraphy, mainly from outcrop studies. Currently, I am focused on outcrop analysis of allochthonous salt emplacement, specifically the transition between vertical diapirism and lateral allochthonous salt spreading. I am also integrating subsurface data from the northern Gulf of Mexico to test the variability in growth strata geometry around passive diapir flanks and better constrain salt evolution and differential rates of salt rise and sedimentation. I have experience with field-based, salt-related research projects in South Australia, Utah, Mexico and northern Spain.

CONTINUING EDUCATION

Nautilus USA, October 2004 - present *Houston, TX*
Sixteen unique field- and classroom-based courses pertinent to petroleum exploration and development (*Course list available on request*)

EDUCATION

Colorado School of Mines, January 2009 - current *Golden, CO*
Ph.D. Candidate Geology (salt tectonics; structural geology), expected Autumn 2013
Advisor: Bruce D. Trudgill
Additional coursework: Economics and Business

New Mexico State University, December 2008 *Las Cruces, NM*
M.S. Geology, *honors graduate* (salt tectonics; structural geology, sedimentology)
Advisor: Timothy F. Lawton

University of the South, May 2003 *Sewanee, TN*
B.S. Geology, *cum laude,* Departmental Honors

University of Pennsylvania geology field camp (YBRA), 2002 *Red Lodge, MT*

PROFESSIONAL EXPERIENCE

Colorado School of Mines, *Research Assistant*, January 2009 - present *Golden, CO*
- Teaching Assistant for undergraduate field mapping course

BP Americas, *Geologist Intern*, February - May 2011 *Houston, TX*
- Western Gulf of Mexico Deepwater Exploration Team (mentor: Bill Hart)
- Structural timing and genesis of a deepwater allochthonous salt keel

Chevron North America, *Geologist Intern*, September - December 2010 *Houston, TX*
- Gulf of Mexico Deepwater Exploration Team, Western Trends (mentor: Steve Holdaway)
- 3D seismic interpretation and structural restorations of complex allochthonous salt systems

New Mexico State University, *Teaching Assistant*, August 2006 - December 2008 *Las Cruces, NM*
- TA courses: Advanced Field Methods, Igneous/Metamorphic Petrology,Field Geology and Physical Geology
- Mapping, field techniques, petrography, hand specimens, lab instruction and tutoring

Woodside Energy, Ltd., *Geologist Intern*, September - December 2007 *Perth, Western Australia*
- International Exploration Team | Santos Basin, Brazil; Ene Basin, Peru
- 2D and 3D seismic interpretation of salt bodies; modeling and structural restorations

Nautilus USA, *Associate Geologist,* October 2004 - May 2006; currently contracting *Houston, TX*
- Managed in-house and field-based geoscience training alliance for consortium of oil companies
- Company representative on field courses operating throughout North America and Europe

Precision Well Logging, *Mudlogging Geologist*, August - October 2004 *Houston, TX*
- Monitored drilling parameters and collected, processed and logged geological samples
- Evaluated data for signs of oil or gas using various laboratory techniques

RECENT PUBLICATIONS AND ABSTRACTS (FULL LIST AVAILABLE UPON REQUEST)

Hearon, T.E., IV, Kernen, R.A., Fiduk, J.C., Rowan, M.G., Trudgill, B.D., 2012, Outcrop analysis of the counterregional-style, partly welded Oladdie diapir, South Australia: American Association of Petroleum Geologists 2012 Annual Convention Abstracts Volume, Long Beach, CA.

Hearon, T.E., IV, Kernen, R.A., Rowan, M.G., Giles, K.A., 2012, Outcrop examples of subsalt structure related to allochthonous salt breakout, Flinders and eastern Willouran Ranges, South Australia: American Association of Petroleum Geologists 2012 Annual Convention Abstracts Volume, Long Beach, CA.

Giles, K.A., Lawton, T.F., Shock, A., Kernen, R,A., **Hearon, T.E., IV**, Rowan, M.G., 2012, A halokinetic drape-fold model for caprock in diapir-flanking and subsalt positions: American Association of Petroleum Geologists 2012 Annual Convention Abstracts Volume, Long Beach, CA.

Kernen, R.A., Giles, K.A., Rowan, M.G., Lawton, T.F., and **Hearon, T.E.,** 2012, Depositional and halokinetic-sequence stratigraphy of the Neoproterozoic Wonoka Formation adjacent to Patawarta allochthonous salt sheet, Central Flinders Ranges, South Australia, in G. I. Alsop, S. G. Archer, A. J. Hartley, N. T. Grant, and R. Hodgkinson, eds., Salt Tectonics, Sedimentation and Prospectivity: London, Geological Society of London Special Publication 363, p. 81-105, doi:10.1144/SP363.5.

Hearon, T.E., IV, Lawton, T.F., Hannah, P.T., 2010, Subdivision of the upper Burra Group in the eastern Willouran Ranges, South Australia: Division of Minerals and Energy Resources of South Australia (MESA) Journal, v. 59, p. 36-46.

PROFICIENCIES & CERTIFICATIONS

Linux and Unix OS, Paradigm Suite, Landmark Suite, LithoTect, 2D Move, Arcview 9.2
Certified Wilderness First Responder (70 hours), Basic CPR/Life Support; AIARE Level 1 Avalanche

AWARDS, HONORS & GRANTS

- ConocoPhillips SPIRIT Scholar ($5000/yr), 2011 - 2013
- BP Scholar Fellowship ($25,000/yr), 2009 - 2012
- Top 10 AAPG Poster Presentation coauthor, 2010
- AAPG Arthur A. Meyerhoff Grant ($3000), 2010
- AAPG Student Poster Presentation Travel Grant ($250), 2008 & 2010
- Rocky Mountain Association of Geologists Norman H. Foster Scholarship ($2500), 2009
- Encana Research Fellowship, 2009
- GSA Student Research Grant ($1650), 2008
- AAPG Gordon I. Atwater Memorial Grant ($2000), 2007
- NMSU Teaching Assistantship, 2006 - 2008
  - Institute of Tectonic Studies Tuition Scholarship, NMSU, 2006 - 2008
- Allen Farmer Forestry and Geology Award, 2003
  - Order of the Gownsmen Academic Honor Society, University of the South, 2001 - 2003
  - Dean's List, 2002
  - Jesse Ball duPont Student Research Grant ($3000), 2002
- Eagle Scout Award - Boy Scouts of America, 1997

PROFESSIONAL MEMBERSHIPS & ACTIVITIES

- American Association of Petroleum Geologists: Technical Session Co-Chair (*Global Salt Tectonics: Models, Outcrops and Case Studies*, 2011; *Exploration in Salt and Deep Water Structural Settings*, 2012); Distinguished Lecturer Committee, 2012-2014
- Geological Society of America, 2001 - present
- Houston Geological Society, 2004 - present
- Society for Sedimentary Geology (SEPM), 2006 - present
- Rocky Mountain Association of Geologists, 2009 – present

Mark P. Fischer
Professor, Graduate Program Director and Assistant Chair
Department of Geology and Environmental Geosciences
Northern Illinois University

EDUCATION

1994 Ph.D. Geology: The Pennsylvania State University, University Park, PA 16802
1989 M.S. Geology: University of Tennessee, Knoxville, TN 37996-1410
1987 B.S. Geology (with distinction): University of Illinois, Urbana, IL 61801

PROFESSIONAL EXPERIENCE

8/07 - present	Professor: Northern Illinois University, DeKalb, IL
8/01 - 8/07	Associate Professor: Northern Illinois University, DeKalb, IL
8/95 - 8/01	Assistant Professor: Northern Illinois University, DeKalb, IL
8/94 - 8/95	Research Geologist: Exxon Production Research Company, Houston, TX
1/94 - 8/94	Post-doctoral Research Associate: The Pennsylvania State University, University Park, PA
5/91- 8/91	Exploration Geologist: Shell Offshore Inc., New Orleans, LA

FUNDED AND PENDING RESEARCH

2012 Collaborative Research: Links between Orogenic Structure and Orogenic Fluid Systems: the Case of the Jura: NSF Tectonics Program – $271,792 *pending*
2005 The Paleohydrologic System near a Salt Diapir and Weld in the La Popa Basin, northeastern Mexico: Petroleum Research Fund – $80,000
2001 Structural Controls on Reservoir Deformation and Compartmentalization in Basement-Involved Fault-Related Folds: Petroleum Research Fund – $119,700
2000 Three-dimensional Geometric Analysis of a Natural Detachment Fold Termination: Nuncios Fold Complex, Sierra Madre Oriental, Mexico: NSF Research Opportunity Program – $15,668
1998 Fluid-Rock System Evolution During Folding: NSF Tectonics Program – $176,342
1997 Critical Assessment of Bedding Curvature as a Fracture Predictor: Petroleum Research Fund – $20,000

SELECTED PUBLICATIONS

2012 Smith, A.P., Fischer, M.P, and Evans, M.E., Fracture-controlled paleohydrology of a secondary salt weld, La Popa Basin, northeastern Mexico, in, Alsop, G.I., Archer, S.G., Hartley, A.J., Grant, N.T. and Hodgkinson, R., eds., *Salt Tectonics, Sediments and Prospectivity: Geological Society of London Special Publication* 363, p. 107-130.

2012 Keating, D.P., Fischer, M.P. and Blau, H., Physical modeling of deformation patterns in monoclines above oblique-slip faults: *Journal of Structural Geology*, in press.

2009 Fischer, M.P., Higuera-Diaz, I.C., Evans, M.E., Perry, E.C. and Lefticariu, L., Fracture-controlled paleohydrology in a map-scale detachment fold: insights from the analysis of fluid inclusions in calcite and quartz veins: *Journal of Structural Geology*, v. 31, no. 12, p. 1490-1510, doi: 10.1016/j.jsg.2009.09.004.

2008 Keating, D.P. and Fischer, M.P., An experimental evaluation of the curvature-strain relation in fault-related folds: *American Association of Petroleum Geologists Bulletin*, v. 92, no. 7, p. 869-884, doi: 10.1306/03060807111.

2006 Fischer, M.P. and Polansky, A., The influence of flaws on joint spacing and saturation: results of one-dimensional mechanical modeling: *Journal of Geophysical Research*, v. 111, B07403, doi: 10.1029/2005JB004115.

2005 Higuera-Diaz, I.C., Fischer, M. P. and Wilkerson, M.S., Geometry and kinematics of the Nuncios detachment fold complex: implications for lithotectonics in northeastern Mexico: *Tectonics*, v. 24, no. 4, TC4010, doi: 10.1029/2003TC001615.

2005 Lefticariu, L., Perry, E.C., Fischer, M.P., and Banner, J.L., Evolution of fluid compartmentalization in a detachment fold complex: *Geology*, v. 33, no. 1, p. 69-72, doi: 10.1130/G20592.1.

2000 Fischer, M.P. and Wilkerson, M.S., Predicting the orientation of joints from fold shape: Results of pseudo-three-dimensional modeling and curvature analysis: *Geology*, v. 28, p. 15-18.

1999 Fischer, M.P. and Jackson, P.B., Stratigraphic controls on deformation patterns in fault-related folds: A detachment fold example from the Sierra Madre Oriental, northeast Mexico: *Journal of Structural Geology*, v. 21, p. 613-633.

1996 Engelder, T. and Fischer, M.P., Loading configurations and driving mechanisms for joints based on the Griffith energy-balance concept: *Tectonophysics*., v. 256, p. 253-277.

1995 Fischer, M.P., Gross, M.R., Engelder, T. and Greenfield, R.J., Finite element analysis of the stress distribution around a pressurized crack in a layered elastic medium: implications for the spacing of fluid–driven joints in bedded sedimentary rock: *Tectonophysics*, v. 247, p. 49-64.

1995 Gross, M.R., Fischer, M.P., Engelder, T., and Greenfield, R.J., Factors controlling joint spacing in interbedded sedimentary rocks: integrating numerical models with field observations from the Monterey Formation, USA, in Ameen, M.S., ed., *Fractography, fracture topography as a tool in fracture mechanics and stress analysis*: Geological Society of London Special Publication 92, p. 215-233.

1994 Engelder, T. and Fischer, M.P., Influence of poroelastic behavior on the magnitude of minimum horizontal stress, S_h, in overpressured parts of sedimentary basins: *Geology*, v. 22, p. 949-952.

1992 Fischer, M.P., Woodward, N.B., and Mitchell, M.M., The kinematics of break-thrust folds: *Journal of Structural Geology*, v. 14, p. 451-460.

GRADUATE STUDENT ADVISING

8/11 – present	Erik Van Dusen (M.S. advisor)
8/10 – present	Phil Kenroy (M.S. advisor)
6/07 – 12/09	Adam Smith (M.S. advisor, graduated 5/10)
8/06 – 12/09	Mike Madison (M.S. advisor, graduated 5/10)
8/00 - 5/03	David Keating (M.S. advisor, graduated, non-thesis option, 5/03)
1/00 - 5/05	I. Camilo Higuera-Diaz (M.S. advisor, graduated 5/05)
8/98 - 8/01	Ryan D. Christensen (M.S. advisor; graduated 8/01)
8/98 - 8/00	Julie A. Malburg (M.S. advisor; graduated, non-thesis option, 8/00)

PROFESSIONAL SOCIETY MEMBERSHIPS

American Association of Petroleum Geologists, member since 2003
Geological Society of America, member since 1987
National Association of Geoscience Teachers, member since 1999
Sigma Xi, The Scientific Research Society, member since 1996

EDUARD ROCA

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SUMMARY

I have a BSc and a PhD in Geology from the Barcelona University, Catalonian and 24 years of industrial and academic experience. After graduating in 1992, I spent a year working at the Institut Français du Pétrole where I conducted research into the hydrocarbon exploration in the Outer Carpathians.

At the beginning of 1993, I joined the University of Barcelona where has been working up to now, first as assistant and, since 2002 as an assistant professor of Structural Geology in the Department of Geodynamics and Geophysics. During this time, I have taught undergraduated and graduated structural geology, basin analysis and geological cartography, and advised graduated students in structural geology, basin analysis, 3D geological reconstructions and salt tectonic projects. Often in collaboration with oil companies, my research projects have been drawn from Europe, South America and North Africa. Also, since 2002, I have conducted training courses on structural geology and salt tectonics for Total, Repsol and the Nautilus Geoscience Training Alliance.

Present-day primary research focus is on salt and inversion tectonics although I continue working in 3D reservoir reconstructions, tectono-sedimentary relationships and the characterization of extensional and contractional fault systems.

EDUCATION

1992 - Ph.D. (with distinction) in Geology, University of Barcelona, Barcelona
Dissertation Title: The structure of the Catalan-Balearic Basin: Role of the contractional and extensional deformation in its formation.
Advisor: P. Santanach

1986 - M.S. (with distinction) in Geology, University of Barcelona, Barcelona
Thesis Title: Geological study of the La Cerdanya Graben (eastern Pyrenees).
Advisor: P. Santanach

PROFESSIONAL MEMBERSHIPS

American Association of Petroleum Geologists, and Sociedad Geológica de España.

SELECTED PROPOSAL RELATED PUBLICATIONS (* denotes student advisees of E. Roca)

Roca, E., Anadón, P., Utrilla, R., and Vázquez, A., 1996, Rise, closure and reactivation of the Bicorb-Quesa evaporite diapir (eastern Prebetics, Spain), Journal of the Geological Society, v. 152, p. 311-321.

Anadón, P., Robles, F., **Roca, E.**, Utrilla, R., and Vázquez, A., 1998, Lacustrine sedimentation in the diapir-controlled Miocene Bicorb Basin, eastern Spain, Palaeogeography Palaeoclimatology Palaeoecology , v. 140, p. 217-243.

Roca, E., Sans, M., and Koyi, H., 2006, Polyphase deformation of diapiric areas in models and in the Eastern Prebetics (Spain), AAPG Bulletin, v. 90, 115-136.

*Ferrer, O., **Roca, E**., Benjumea, B., Muñoz, J.A., Ellouz., and MARCONI Team., 2008, The deep seismic reflection MARCONI-3 profile: Role of extensional Mesozoic structure during the Pyrenean contractional deformation at the eastern part of the Bay of Biscay**,** Marine and Petroleum Geology, v. 25, p. 714-730.

*Ferrer, O., Vendeville, B.C., and **Roca, E**., 2008, Influence of a syntectonic viscous salt layer on the structural evolution of extensional kinked-fault systems, Bollettino Di Geofisica Teorica Ed

Applicata, v. 49, p. 371-375.

Vidal-Royo, O., *Ferrer, O., Koyi, H.A., Vendeville, B.C., Muñoz, J.A., and **Roca, E**., 2008, 3D reconstruction of analogue modelling experiments from 2D datasets, Bollettino Di Geofisica Teorica Ed Applicata, v. 49, p. 524-528.

*Rubinat, M., Ledo, J.J., **Roca, E.**, Rosell, O., and Queralt, P., 2010, Magnetotelluric characterization of a salt diapir: a case study on Bicorb-Quesa Diapir (Prebetic Zone, SE Spain), Journal of the Geological Society, v. 167, p. 145-153.

Roca, E., Muñoz, J.A., *Ferrer, O, and Ellouz, N., 2011, The role of the Bay of Biscay Mesozoic extensional structure in the configuration of the Pyrenean orogen: Constraints from the MARCONI deep seismic reflection survey, Tectonics, v. 30, doi:10.1029/2010TC002735

*Ferrer, O.; Jackson, M.P., **Roca, E.**, and *Rubinat, M., 2012, Evolution of salt structures during extension and inversion of the Offshore Parentis Basin (Eastern Bay of Biscay, *in* Alsop, G. I., et al.(eds), Salt Tectonics, Sediments and Prospectivity; Geological Society of London Special Publications, v. 363, p. 521-532.

*Quintà, A., Tavani, S., and **Roca, E.**, 2012. Fracture pattern analysis as a tool for constraining the interaction between regional and diapir-related stress fields. The example of the Poza de la Sal diapir (Basque Pyrenees, Spain). *in* Alsop, G. I., et al.(eds), Salt Tectonics, Sediments and Prospectivity; Geological Society of London Special Publications, v. 363, p. 521-532.

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EDUCATION

Degree in Geology	University of Barcelona	1981
Master in Geology	University of Barcelona	1982
PhD in Geology	University of Barcelona	1985

CARRIER/EMPLOYMENT

2003-present Full Professor at University of Barcelona
Professor at University of Barcelona
Technical Collaborator at the Catalonian Geological Survey
1982-1984 PhD fellowship at the University of Barcelona

SCIENTIFIC ACTIVITIES

Experience on thrust tectonics, tectonic inversion, extensional tectonics, salt tectonics, tectono-sedimentation relationships, balancing techniques, 3D reconstruction and modeling of geological structures and reservoir characterization.
Currently working in structural geology projects in the Pyrenees, northern Chilean and Argentinean Andes. Also working in salt tectonics in the Cantabrian Pyrenees, 3D structural reconstructions of fault related folds and associated fracture patterns for reservoir characterization purposes and detailed construction of 3D geological models.

SELECTED PUBLICATIONS

MUÑOZ, J.A.; MARTÍNEZ, A.; VERGES, J. 1986. Thrust sequences in the eastern Spanish Pyrenees. *Journal of Structural Geology*, 8 (3-4): 399-405.
ROURE, F.; CHOUKROUNE, P.; BERASTEGUI, X.; MUÑOZ, J.A. et al. 1989. ECORS deep seismic data and balanced cross sections - geometric constraints on the evolution of the Pyrenees. *Tectonics*, 8: 41 – 50.
BURBANK, D.; VERGÉS, J.; MUÑOZ, J.A.; BENTHAM, P. 1992. Coeval hindward -and forward-imbricating thrusting in the central southern Pyrenees, Spain: timing and rates of shortening. *Geological Society of America Bulletin*, 104: 3-17.
MUÑOZ, J.A. 1992. Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. In: *Thrust Tectonics* (ed. by K.McClay). Editorial Chapman & Hall. 235-246.
MUÑOZ, J.A.; McCLAY, K. & POBLET, J. 1994. Synchronous extension and contraction in frontal thrust sheets of the Spanish Pyrenees. *Geology*, 22: 921-924.
CONEY, P.J.; MUÑOZ, J.A.; McCLAY, K.R. & EVENCHICK, C. 1996. Syntectonic burial and post-tectonic exhumation of the southern Pyrenees foreland fold-thrust belt. *Journal of the Geological Society, London*, 153, 9-16.
SANS, M.; MUÑOZ, J.A.; VERGÉS, J. 1996. Triangle zone and thrust wedge geometries related to evaporitic horizons (southern Pyrenees). *Bulletin of Canadian Petroleum Geology*, 44 (29): 375-384.
SUPPE, J.; SABAT, F.; MUÑOZ, J.A.; POBLET, J.; ROCA, E.; VERGES, J. 1997. Bed-by-bed fold growth by kink-band migration: Sant Llorenç de Morunys, Eastern Pyrenees. Journal of Structural Geology, 19 (3-4): 443-461.
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POBLET, J.; MUÑOZ, J.A.; TRAVE, A. & SERRA-KIEL, J. 1998. Quantifying the kinematics of detachment folds using the three-dimensional geometry: application to the Mediano anticline (Pyrenees, Spain). *Geological Society of America Bulletin*, 110(1):111-125.
FITZGERALD, P.G.; MUÑOZ, J.A.; CONEY, P.J. & BALDWIN, S.L. 1999. Asymmetric exhumation across the central Pyrenees: implications for the tectonic evolution of a collisional orogen. *Earth and Planetary Science Letters*, 173: 157-170.
BEAUMONT, C.; MUÑOZ, J.A.; HAMILTON, J. & FULLSACK, P. 2000. Factors controlling the Alpine Evolution of the Central Pyrenees inferred from a comparison of observations and geodynamical models. *Journal of Geophysical Research*, 105 (B4): 8121-8145.
FERNÁNDEZ, O.; MUÑOZ, J.A.; ARBUÉS, P. 2003. Quantifying and correcting errors derived from apparent dip in the construction of dip-domain cross-sections. Journal of Structural Geology, 25: 35-42.
BEAMUD, E.; GARCÉS, M., CABRERA, L.; MUÑOZ, J. A.; ALMAR, Y. 2003. A new middle to late Eocene continental chronostratigraphy from NE Spain. Earth and Planetary Science Letters, 216: 501-514
MCCLAY, K.; MUÑOZ, J. A.; GARCÍA-SENZ, J. 2003. Extensional salt tectonics in a contractional orogen: faulting: A newly identified tectonic event in the Spanish Pyrenees. Geology, 32 (9): 737-740.
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TAVANI, S., STORTI, F., FERNÁNDEZ, O., MUÑOZ, J.A., SALVINI, F. 2006. 3-D deformation pattern analysis and evolution of the Añisclo anticline, southern Pyrenees. Journal of Structural Geology, 28: 695-712.
CARRERA, N., MUÑOZ, J.A., SÀBAT, F., MON, R., ROCA, E. 2006. The role of inversion tectonics in the structure of the Cordillera Oriental (NW Argentinean Andes). Journal of Structural Geology
CARRERA, N.; MUÑOZ, J.A. 2008 Thrusting evolution in the southern Cordillera Oriental (northern Argentine Andes): Constraints from growth strata. Tectonophysics, 459 (1-4) 107-122
HARDY, S.; McCLAY KR.; MUÑOZ, J.A. 2009. Deformation and fault activity in space and time in high-resolution numerical models of doubly vergent thrust wedges. Marine and Petroleum Geology, 26 (2) 232-248
CARRERA, N., MUÑOZ, J.A. ROCA, E., 2009. 3D reconstruction of geological surfaces by the equivalent dip-domain method: an example from field data of the Cerro Bayo Anticline (Cordillera Oriental, NW Argentine Andes). Journal of Structural Geology, 31(12): 1573-1585.
VIDAL-ROYO, O; KOYI, H.A.; MUÑOZ, J.A., 2009. Formation of orogeny-perpendicular thrusts due to mechanical contrasts in the basal décollement in the Central External Sierras (Southern Pyrenees, Spain); Journal of Structural Geology, 31: 523-539.
ROCA. E., MUÑOZ, J.A., FERRER, O., ELLOUZ, N., 2010. The role of the Bay of Biscay Mesozoic extensional structure in the configuration of the Pyrenean orogen: Constraints from the MARCONI deep seismic reflection survey. Tectonics.
SNIDERO, M.; AMILIBIA, A.; GRATACÓS, O.; BLANC, E.J.;MUÑOZ, J.A., 2011. The 3D reconstruction of geological structures based on remote sensing data: example from Anaran anticline, Lurestan province, Zagros fold and thrust belt, Iran. Journal of the Geological Society, 168: 769-782.

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Summary

I have thirty years of combined exploration, production, research, and service company experience in the petroleum industry and academia. I have conducted research projects in many areas of the world including offshore Brazil, Libya, West Africa, the northern Gulf of Mexico, the Permian Basin of West Texas and eastern New Mexico, the North Sea, the Alaskan North Slope, north-central Texas, the San Juan Basin, the Illinois Basin, the South Florida Basin, the western Gulf of Mexico, and the Mexican southern Gulf of Mexico. I have worked on the structural and stratigraphic evolution of various fold belts and modeled the petroleum systems in the Gulf of Mexico. My projects include using 3-D immersive visualization, depth image processing and interpretation of 3-D time and depth data for research and exploration. I have managed the resources and people for multiple projects over the past ten years and regularly consultant to the company's clientele as needed.

Professional Experience

Chief Geologist	
(7/10— present).	WesternGeco, 10001 Richmond Ave., Houston, TX 77042
Chief Geologist	
(6/02—7/10).	CGGVeritas, 10300 Town Park Dr., Houston, Texas 77072
Consulting Geophysicist	
(9/96—6/02).	4215 Evans Dr., Boulder, Colorado 80303
Special Consultant to **bp** Center for Visualization	
(8/00-2/01).	Department of Aerospace Engineering, University of Colorado, Boulder, CO 80309.
Research Associate	
(9/94-8/96).	Department of Geological Sciences, the University of Colorado, Boulder, CO 80309.
Research Assistant	
(9/93-8/94, 10/91-12/92, 1/87-2/88).	Bureau of Economic Geology, Fiduk, J. C., University Station Box X, Austin, TX 78713.
Research Associate	
(9/89-6/92, 1/89-6/89, 1/88-9/88).	Geophysics Department, Texas A&M University, College Station, TX 77843.
Intern Geophysicist	
(6/89-9/89).	British Petroleum Exploration Co., P.O. Box 4587, Houston, TX 77210.
Research Assistant	
(6/88-12/88).	Department of Geological Sciences, University Texas at Austin, Austin, TX 78712.
Well Site Geologist	
(9/85-12/85).	Discovery Logging Inc., P.O. Box 80531, Midland, TX 79708.
Petroleum Geophysicist	
(1/82-6/85).	Gulf Oil Exploration & Production Co., P.O. Box 1150, Midland, TX 79708.
Hydrologic Field Assistant - GS 7	
(6/80-9/80).	United States Geological Survey, Orlando, FL
Field Technician - GS 7	
(6/79-9/79).	United States Geological Survey, Orlando, FL.

Education

1986-1994	Ph D. Geology, University of Texas at Austin -- G.P.A. 3.78
Topic	Plio-Pleistocene evolution of the upper continental slope in the Garden Banks and East Breaks OCS areas, northwest Gulf of Mexico
1982-1985	M.B.A. University of Texas of the Permian Basin -- G.P.A. 3.81
1979-1982	M.S.Geology, University of Florida -- G.P.A. 3.77
Topic	Uranium and Thorium geochemistry in Late Archean rocks of the Bear Tooth Mountains, Wyoming and Montana
1975-1979	B.S. Geology, University of Florida -- G.P.A. 3.0

Recent Publications

Hearon, T.E., R. Kernen, C. Fiduk, M.G. Rowan, and B.D. Trudgill, 2012 in press, Outcrop analysis of the counter-regional-style, partly welded Oladdie diapir, South Australia: 2012 AAPG Annual Convention Abstract vol., p.xxx.

Fiduk, J. Carl and Mark G. Rowan, 2012, Analysis of folding and deformation within layered evaporites in Blocks BM-S-8 & -9, Santos Basin, Brazil: Geological Society, London, Special Publications 2012, v. 363, p. 471-487.

Fiduk, J. C., 2010, Analysis of Layered Evaporites within the Santos Basin, Brazil: 2010 Offshore Technology Conference, May 3-6, Houston, Texas, USA, p. 1-5, OTC 20938.

Fiduk, Joseph C., Lynn E. Anderson, and Mark G. Rowan, 2010, The structural control of South Texas Upper Wilcox shelf margin and slope facies deposition by extensional rafting: salt tectonic and petroleum exploration implications: Contributions to South Texas Geology, p. 174-193.

Fiduk, Joseph C., 2010, Examination of the Libyan Mediterranean margin using regional 2-D seismic data (abs): AAPG 2010 Annual Convention Abstract vol., p. 77-78.

Fiduk, Joseph Carl, 2010, Deformation of Layered Evaporites within the Santos Basin, Brazil: Geological Society of London - SEPM international conference on "Salt tectonics, sediments and prospectivity", January 20-22, 2010, Burlington House, Piccadilly, London, UK, program with abstracts, p.26.

Fiduk, J. C., 2009, Evaporites, Petroleum Exploration, and the Cenozoic Evolution of the Libyan Shelf Margin, Central North African: Marine and Petroleum Geology, v. 26, p. 1513-1527.

Fiduk, Joseph C., Lynn E. Anderson, and Mark G. Rowan, 2009, The structural control of South Texas Upper Wilcox shelf margin and slope facies deposition by extensional rafting: salt tectonic and petroleum exploration implications: Bulletin of the South Texas Geological Society, vol. 49, no. 7, p. 13-36.

Fiduk, J. C., and Andrew J. Pulham, 2008, Structural Control and Stratigraphic Architecture of Recent Discoveries and Producing Fields in the Central Northern Gulf of Mexico: Extended Abstracts Volume, AAPG International Conference (Cape Town, South Africa, October 26-29, 2008) unpaginated CD.

Fiduk, J. C., Lynn E. Anderson, Thomas R. Schultz, and Andrew J. Pulham, 2007, Deep-water depositional trends of the Cretaceous and Paleogene in the Central northern Gulf of Mexico (ext abs): Proceedings of the Twenty-seventh Annual Gulf Coast Section SEPM Foundation Bob F. Perkins Research Conference, December 2-5, 2007, p. 45-53.

Fiduk, J. Carl, Lynn E. Anderson, and Thomas R. Schultz, 2007, Salt sediment interaction offshore Libya (abs): Proceedings of the 1st Moroccan Association of Petroleum Geologists Conference, October 28-31, 2007, p. 16.

Including the listed papers I have 70+ publications, 30+ of which are invited papers. I have an equal number of public oral presentations to professional and academic audiences.

Concepts in halokinetic-sequence deformation and stratigraphy

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Abstract: Halokinetic sequences are unconformity-bound packages of thinned and folded strata adjacent to passive diapirs. Hook halokinetic sequences have narrow zones of deformation (50–200 m), >70° angular discordance, common mass-wasting deposits and abrupt facies changes. Wedge halokinetic sequences have broad zones of folding (300–1000 m), low-angle truncation and gradual facies changes. Halokinetic sequences have thicknesses and timescales equivalent to parasequence sets and stack into composite halokinetic sequences (CHS) scale-equivalent to third-order depositional cycles. Hook sequences stack into tabular CHS with sub-parallel boundaries, thin roofs and local deformation. Wedge sequences stack into tapered CHS with folded, convergent boundaries, thicker roofs and broad zones of deformation. The style is determined by the ratio of sediment-accumulation rate to diapir-rise rate: low ratios lead to tabular CHS and high ratios result in tapered CHS. Diapir-rise rate is controlled by the net differential load on deep salt and by shortening or extension. Similar styles of CHS are found in different depositional environments but the depositional response varies. CHS boundaries (unconformities) develop after prolonged periods of slow sediment accumulation and so typically fall within transgressive systems tracts in shelf settings and within highstand systems tracts in deepwater settings. Sub-aerial settings may lead to erosional unroofing of diapirs and consequent upward narrowing of halokinetic deformation zones.

It has long been recognized from both surface and subsurface data that strata flanking passively growing salt diapirs typically thin and upturn near the diapir and locally contain angular unconformities (e.g. Bornhauser 1969; Johnson & Bredeson 1971; Steiner 1976; Lemon 1985; Davison *et al.* 2000). The angular unconformities define bounding surfaces separating genetically related packages of halokinetic growth strata termed halokinetic sequences (Giles & Lawton 2002). Halokinetic sequences were defined by Giles & Lawton (2002) as 'relatively conformable successions of growth strata genetically influenced by near-surface or extrusive salt movement and are locally bounded at the top and base by angular unconformities that become disconformable to conformable with increasing distance from the diapir'. Halokinetic sequences are generated by changes in net diapir-rise rate v. net local sediment-accumulation rate (Giles & Lawton 2002; Rowan *et al.* 2003). Rowan *et al.* (2003) modelled the upturn of beds within halokinetic sequences as the result of drape folding (also termed flap folding by Schultz-Ela 2003) over the edge of a passive diapir that is rising with respect to the adjacent minibasin. Build-up of topographic relief and erosional truncation of the rotated beds generate a surface that is subsequently onlapped and overlapped, producing an angular unconformity. The angular unconformities and onlap surfaces become zones of concentrated slip during flexural-slip folding and the degree of angular discordance increases in the shallow subsurface with continued halokinesis (Rowan *et al.* 2003). The space created by rotation of the beds and slip on the unconformity is passively filled by salt, often creating a cusp in the margin of the salt diapir where it is intersected by the unconformity.

In this paper we define two end-member types of halokinetic sequences that stack stratigraphically into two types of larger-scale stratigraphic packages, referred to here as composite halokinetic sequences. In focusing on composite halokinetic sequences, we first describe their geometric attributes and then present outcrop and seismic examples of composite halokinetic sequences developed in three different depositional environments: shallow-water shelf settings, deepwater slope and basinal settings and sub-aerial settings. Similarities and key differences recognized between the different depositional settings allow us to identify the controlling factors and discuss general implications for depositional facies. We then use these relationships to formulate a genetic model for the formation of the different halokinetic-sequence and composite halokinetic-sequence types. Finally, we discuss

From: Alsop, G. I., Archer, S. G., Hartley, A. J., Grant, N. T. & Hodgkinson, R. (eds) 2012. *Salt Tectonics, Sediments and Prospectivity*. Geological Society, London, Special Publications, **363**, 7–31. http://dx.doi.org/10.1144/SP363.2

variations on the model and contrast composite halokinetic sequences with superficially similar larger-scale geometries produced by regional shortening or differential subsidence of minibasins. The halokinetic-sequence and composite-sequence models presented here provide important tools for predictions of trap geometries, reservoir character and distribution, seal and hydrocarbon migration in salt diapir-flank traps.

Classification of halokinetic sequences and composite halokinetic sequences

We recognize two end-member types of halokinetic sequences, referred to here as hook and wedge halokinetic sequences (Fig. 1). The two types are defined geometrically, with different drape-fold geometries and degree of angular discordance at the bounding unconformities. The distinction is based mostly on outcrop patterns in La Popa Basin, Mexico, but also on those in the Flinders and Willouran ranges of South Australia. Furthermore, the Mexican examples suggest that hook and wedge halokinetic sequences are equivalent in scale to depositional parasequence sets and form packages tens of metres in thickness.

Hook halokinetic sequences have narrow and steep drape-fold geometries (Fig. 1a). Beds fold and thin over a distance of 50–200 m from the diapir with bed rotation of up to, but not surpassing, 90°. Bounding unconformities are correspondingly highly angular (>70°) with up to 90° of angular discordance, but become conformable within 200 m of the diapir. In contrast, wedge halokinetic sequences have broad and gentle drape-fold geometries (Fig. 1b). Folding and thinning occur over a wider zone of 300–1000 m, with only minor and gradual bed rotation. Bounding unconformities have low-angle truncation (<30° and, more typically, 5–10°), but commonly extend for more than 500 m away from the diapir before becoming conformable.

Halokinetic sequences stack stratigraphically into two end-member types of composite sequences, referred to here as tabular and tapered. Again, they are defined based on stratal geometries both from field exposures in Mexico and South Australia and from subsurface seismic analogues in various basins. Composite sequences form packages hundreds of metres in thickness. Age control in both La Popa Basin and the northern Gulf of Mexico suggests that composite halokinetic sequences correspond in duration to third-order depositional sequences, ranging from several hundred thousand years to several millions of years.

Tabular composite halokinetic sequences (tabular CHS) form by vertically stacking hook sequences (Fig. 2a), creating a large-scale package with tabular form (upper and lower bounding surfaces are parallel to sub-parallel). Stratal thinning and drape-fold upturn of individual sequences take place within 200 m of the diapir. The axial traces of drape-fold monoclines within individual hook halokinetic sequences are slightly offset from each other at the halokinetic sequence boundaries, but are confined to a narrow zone trending roughly parallel to and close to the diapir margin. Minor cusps form where the unconformities intersect the diapir. In contrast, tapered composite halokinetic sequences (tapered CHS) form by stacking wedge sequences (Fig. 2b), creating a large-scale package with a

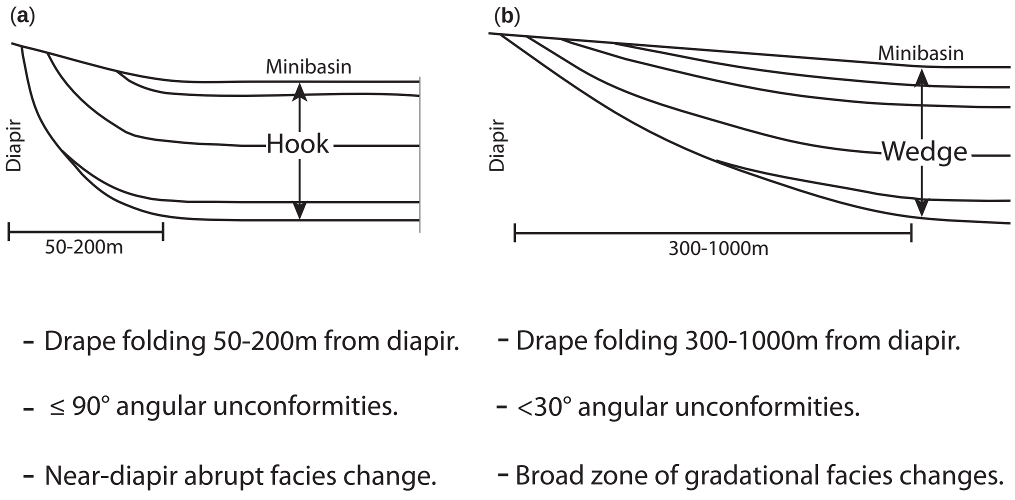
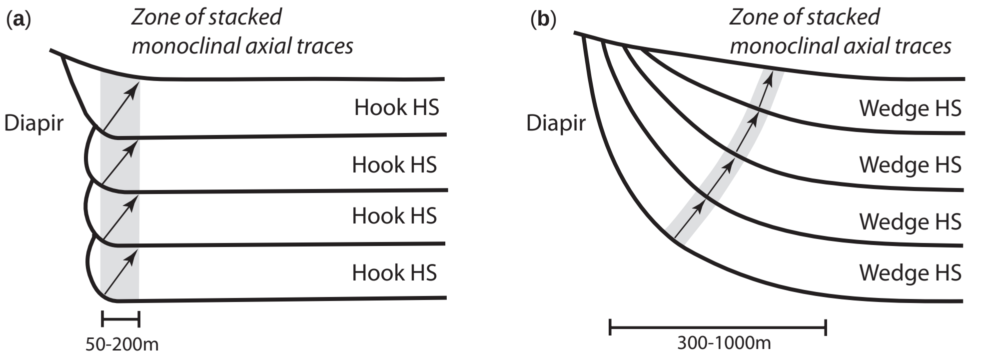


Fig. 1. Two end-member types of halokinetic sequences: (**a**) hook halokinetic sequence; and (**b**) wedge halokinetic sequence.



- Subparallel base and top boundaries.
- Narrow zone of thinning near diapir.
- Axial trace of monocline near diapir & forms zone parallel to diapir margin.

- Convergent base and top boundaries.
- Broad zone of thinning toward diapir.
- Axial trace of monocline progressively inclined from diapir.

Fig. 2. Two end-member types of composite halokinetic sequences (CHS): (**a**) tabular CHS; and (**b**) tapered CHS.

broadly folded tapered form (upper and lower bounding surfaces gradually converge towards the diapir). The lower boundary is folded over a distance of 300–1000 m from the diapir so that thinning towards the diapir occurs over a wide zone. The axial traces of stacked drape-fold monoclines trend at an incline away from the margin of the diapir and are slightly curved. Although individual wedge sequences have low-angle unconformities, the lower wedges in a tapered CHS exhibit high-angle truncation beneath the composite halokinetic-sequence boundary.

Surface and subsurface examples

The geometries described above are recognized in a wide variety of depositional environments. Halokinetic-fold styles are similar in different settings because the deformation processes are similar, but there are also some key differences (especially in the depositional response to drape folding). In the following sections, we examine a combination of surface and subsurface data from shallow-marine shelf settings, deep-marine slope and basinal settings and sub-aerial settings.

Shallow-marine shelf settings (examples from La Popa Basin, Mexico)

Halokinetic deformation of shallow-water sediments with local thinning, folding and recycling of diapir and roof material is known from a number of basins including the Fars Province of Iran (Jahani *et al.* 2007), the Flinders Ranges of South Australia (e.g. Lemon 1985; Dyson 1998), the Basque Pyrenees of Spain (J. A. Muñoz pers. comm. 2009) and onshore South Louisiana (e.g. Johnson & Bredeson 1971). However, both types of halokinetic sequences and composite halokinetic sequences have been documented in the well-exposed Cretaceous through Palaeogene strata of La Popa salt basin of NE Mexico (Giles & Lawton 2002; Rowan *et al.* 2003; Aschoff & Giles 2005; Giles *et al.* 2008).

La Popa Basin (Fig. 3) contains an estimated 7000 m of Lower Cretaceous through Palaeogene strata, all of which form halokinetic sequences adjacent to three exposed salt diapirs (El Gordo, El Papalote and La Popa Weld, formerly a salt wall). The presence of halokinetic sequences indicates ongoing passive diapirism throughout deposition of the strata. The salt diapirs arise from the Jurassic (Oxfordian) Minas Viejas Formation. The bulk of exposed strata in the basin comprise the Parras Shale and the overlying Difunta Group (containing, in ascending order, the Muerto, Potrerillos, Adjuntas, Viento and Carroza formations). These marine to non-marine, dominantly siliciclastic units were deposited within the distal part of the Upper Cretaceous to Palaeogene Hidalgoan/Laramide foreland basin system that includes the Parras Basin and the adjacent Sierra Madre Oriental fold–thrust belt to the south (Dickinson & Lawton 2001; Lawton *et al.* 2001). Hidalgoan shortening deformed all exposed strata in La Popa Basin into NW–SE trending folds forming the Coahuila marginal fold belt (Wall

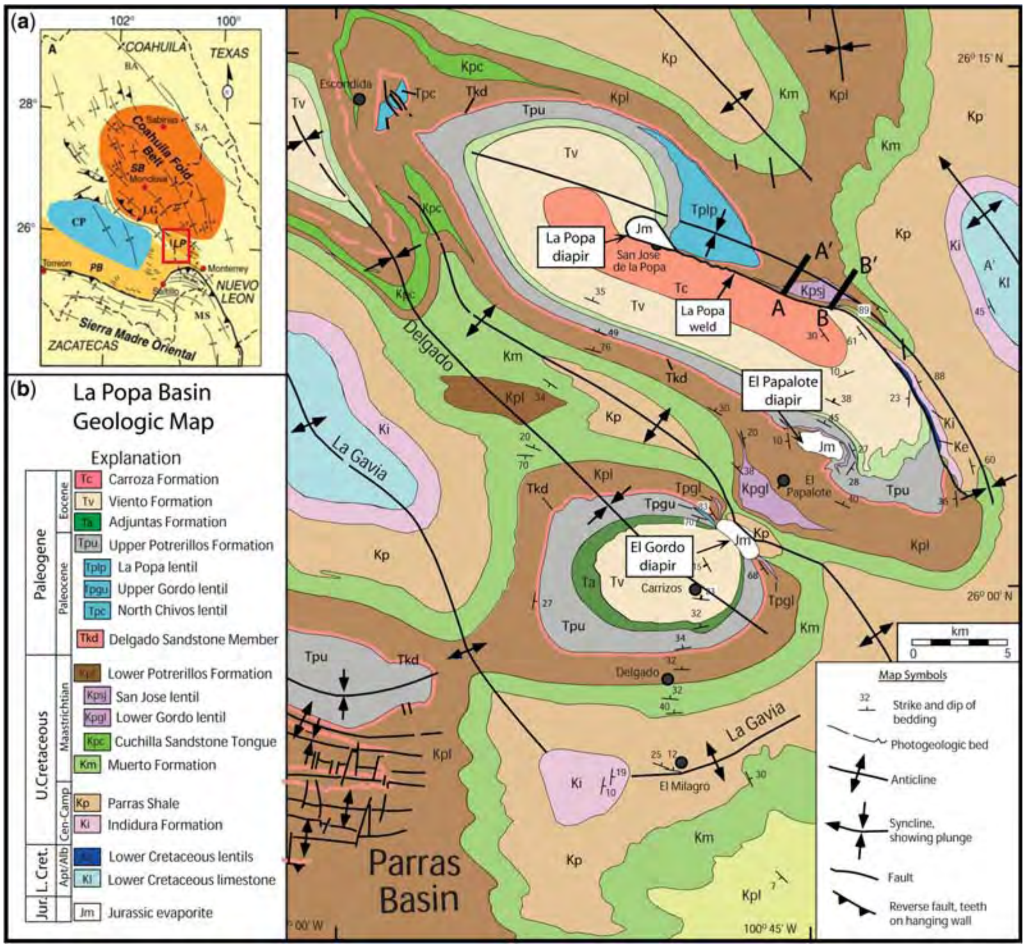


Fig. 3. Maps of La Popa Basin area in NE Mexico: (**a**) geographic location map of La Popa Basin (LP) in NE Mexico; and (**b**) geological map; location of cross sections A–A′ (Fig. 4) and B–B′ (Fig. 5) are shown. Figure modified from Lawton *et al.* (2001).

et al. 1961). In La Popa Basin, shortening initiated in the late Maastrichtian during deposition of the Middle Siltstone Member of the Potrerillos Formation (Druke 2005; Lawton *et al.* 2005; Giles *et al.* 2008); the uppermost Cretaceous and Palaeogene part of La Popa Basin sedimentary fill was therefore deposited while contraction was ongoing. Two of the diapirs (El Gordo and La Popa Weld) are along major shortening structures; the other (El Papalote) is within a fold limb and has therefore experienced much less shortening than the others (Rowan *et al.* 2003, 2012).

Hook halokinetic sequences are well developed in both the Lower Mudstone and Upper Mudstone members of the Potrerillos Formation at all three diapirs and within the Middle Siltstone Member at La Popa Weld. The mudstones represent the deepest-water facies in La Popa Basin (outer-shelf hemipelagic black shales) and presumably the slowest overall sediment-accumulation rates. The Middle Siltstone Member comprises prodeltaic mudstone and siltstone deposited in a middle-shelf setting, and represents slightly shallower water conditions than the mudstone members and presumably slightly higher sedimentation rates (Druke 2005). Internally, hook halokinetic sequences follow a repetitive upwards facies progression (Fig. 4). Near-diapir basal deposits above the halokinetic sequence boundaries comprise carbonate debris-flow facies that contain clasts in a silty to sandy carbonate matrix.

Debris-flow clasts were derived from both non-evaporite lithologies present within the diapirs, such as meta-igneous blocks (Garrison & McMillan 1999), and from diapir roof sediments which in this

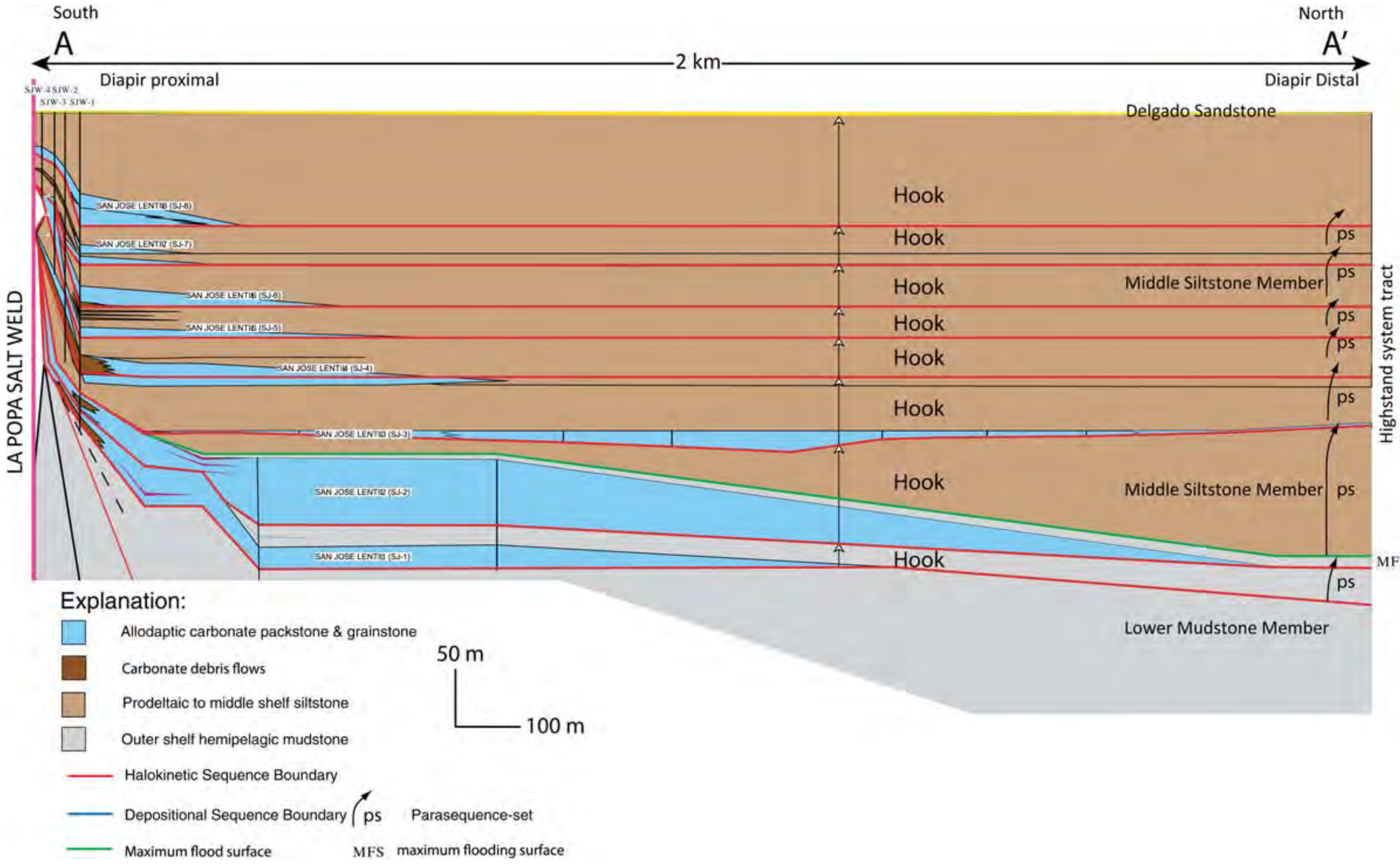


Fig. 4. Stratigraphic cross-section A–A′ showing hook halokinetic sequences and tabular CHS developed in the Lower Mudstone and Middle Siltstone members of the Potrerillos Formation on the north side of La Popa Weld, La Popa Basin, Mexico. Location of section shown in Figure 3. Figure modified from Druke (2005).

setting were dominantly shallow-water, diapir-isolated marine carbonate facies such as oyster and red algal-rich packstones and local sponge, coral and red algal patch reefs (Hunnicutt 1998; Mercer 2002; Druke 2005). The diapir-derived debris flows are thickest near the diapir and thin away from it, but typically do not extend more than a few hundred metres away from the diapir. The debris flows are commonly overlain by or interbedded with allodaptic limestone (packstone and grainstone) that represents carbonate sediments generated in shallow water on top of the inflated diapir and subsequently transported down the flanks by gravity-driven grain and turbidity flows (Giles *et al.* 2008). The carbonate debris flows and allodaptic limestone are collectively referred to as carbonate lentils (Laudon 1975) because of their diapir-centric distribution.

Open-shelf and lower-shoreface fine-grained sandstone sometimes thin and onlap onto the basal carbonate facies, but generally do not overlap the diapir. In hook sequences within the Upper Mudstone Member at El Papalote Diapir, these sandstones are interpreted as deposition from hyperpycnal flows (Druke & Giles 2008). In all cases, the sequence finishes with middle- to outer-shelf black shale or siltstone that thins onto and overlaps the diapir. We infer that topographic relief built up during prolonged, slow deposition of the black-shale facies, forming steep unstable slopes that eventually failed and produced debris flows. The failure scarp formed an angular unconformity commonly directly overlain by mass-wasting deposits, that is, the base of the next hook halokinetic sequence. Hook sequences typically range in thickness from 25 m to a little over 100 m, with folding and thining in a narrow zone 50–200 m wide (Fig. 4). Hook sequences are interpreted to have been deposited at a parasequence to parasequence-set scale (Druke & Giles 2008; Giles *et al.* 2008).

Wedge halokinetic sequences are well developed within the Muerto Formation at La Popa Weld (Fig. 5). The Muerto Formation comprises siltstone to medium-grained sandstone with rare chert-pebble conglomerates deposited within a prograding deltaic system (Hon 2001; Weislogel 2001). The siliciclastic strata represent shallow-shelf/prodeltaic siltstones and lower-shoreface to foreshore or tidal sandstones organized into progradational-parasequence sets that suggest relatively high sediment-accumulation rates. The repetition of facies within an individual wedge halokinetic sequence starts within lower- to middle-shoreface sandstone parasequences that onlap the halokinetic sequence boundary (Fig. 5). The parasequences display a progradational stacking pattern shallowing up to upper-shoreface and tidal/coastal-plain parasequences at the top of the parasequence set. These are capped by major flooding surfaces that are in turn overlain by shallow shelf/prodeltaic siltstones.

Muerto wedge successions lack the debris-flow conglomerates containing diapir-derived detritus that are a common component of hook halokinetic sequences, suggesting the diapir was buried beneath a roof comprising mostly Parras Shale. Erosional unconformities are nevertheless present, but we infer a different origin than the slump failure dominant in hook sequences. Topographic relief over the diapir probably built up during periods of slower deposition of the shallow-shelf/prodeltaic siltstone so that near-diapir strata may have been elevated into a shoreface environment. Shoreface wave erosion over the slightly inflated diapir likely cut the angular unconformity surfaces that were then onlapped by lower- to upper-shoreface sandstones of the next wedge halokinetic sequence. Muerto wedge halokinetic sequences typically range from 50 to 100 m in thickness, thin over a distance of 400–600 m and were deposited at a parasequence-set timescale (Hon 2001).

Individual hook and wedge halokinetic sequences stack into tabular and tapered composite halokinetic sequences, respectively, at La Popa Weld and El Papalote Diapir (Figs 6 & 7). In the shelf setting of La Popa Basin, tapered CHS generally formed during the highstand systems tract and (if present) the lowstand systems tract, when siliciclastic sediment influx to the shelf increased due to shoreline regression (either normal or forced). Examples include the Parras and Muerto formations and the lowest part of the Lower Siltstone Member of the Potrerillos Formation at La Popa Weld (Fig. 6) and the Middle Siltstone to Delgado members and the Upper Sandstone Member of the Potrerillos Formation at El Papalote Diapir (Fig. 7).

Note that in the Parras-Lower Siltstone system at the weld the succession becomes increasingly more sand-prone upwards as regression progressed. It then becomes less sand-prone in the uppermost part of the tapered CHS, as sediment influx slowed and topographic relief built up again into a zone of erosional truncation and generation of the upper composite halokinetic-sequence boundary (Fig. 6). Also note that the sandiest strata (Muerto Formation) do not extend to the weld, but are separated from it by several hundred metres. The pinch-out of sand-prone facies towards the diapir reflects both depositional thinning and erosional truncation (Hon 2001) over a wider zone of topographic relief than documented in hook successions.

In La Popa basin there are two exceptions to the correlation of tapered CHS and highstand systems tracts in shelf settings. First, the Middle Siltstone Member, which formed a tapered CHS at El Papalote Diapir (Fig. 7), formed a tabular CHS at La Popa Weld (Fig. 6) even though overall net

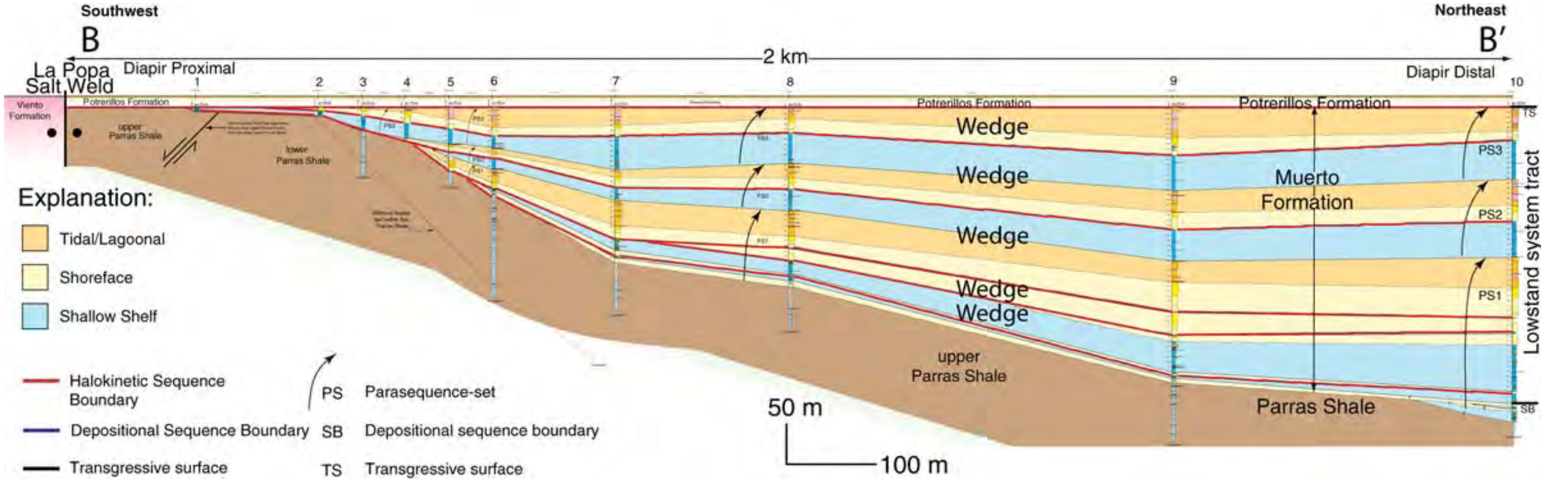
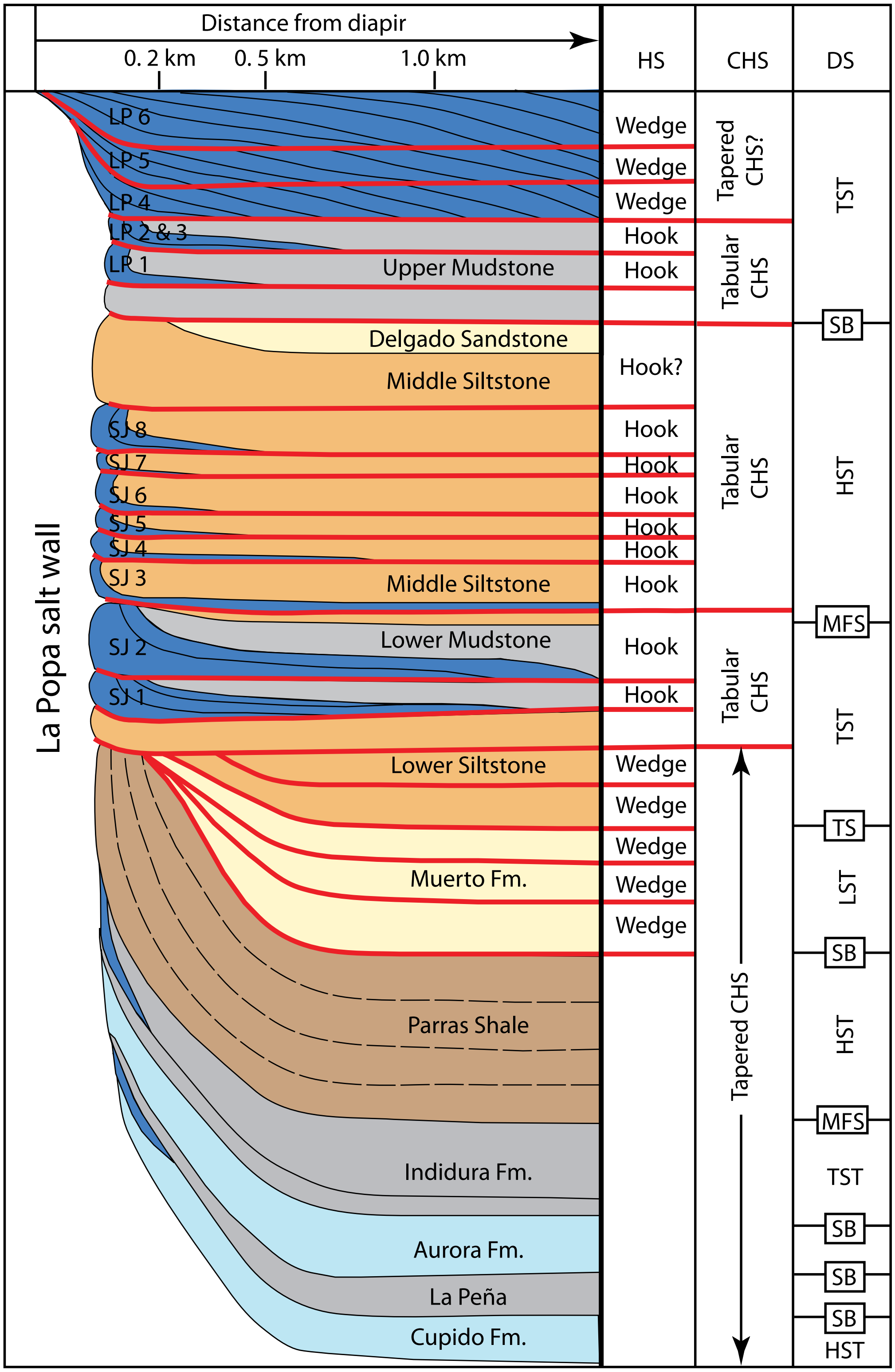


Fig. 5. Stratigraphic cross-section B–B′ showing wedge halokinetic sequences and tapered CHS developed in the Muerto Formation on the north side of La Popa Weld, La Popa basin, Mexico. Location of section shown on Figure 3. Figure modified from Hon (2001).


Distance from diapir
0. 2 km
0. 5 km
1.0 km
HS
CHS
DS
LP 6
LP 5
LP 4
LP 2 & 3
LP 1
Upper Mudstone
Delgado Sandstone
Middle Siltstone
SJ 8
SJ 7
SJ 6
SJ 5
SJ 4
SJ 3
Middle Siltstone
SJ 2
Lower Mudstone
SJ 1
Lower Siltstone
Muerto Fm.
Parras Shale
Indidura Fm.
Aurora Fm.
La Peña
Cupido Fm.
La Popa salt wall
Wedge
Wedge
Wedge
Hook
Hook
Hook?
Hook
Hook
Hook
Hook
Hook
Hook
Hook
Hook
Wedge
Wedge
Wedge
Wedge
Wedge
Tapered CHS?
Tabular CHS
Tabular CHS
Tabular CHS
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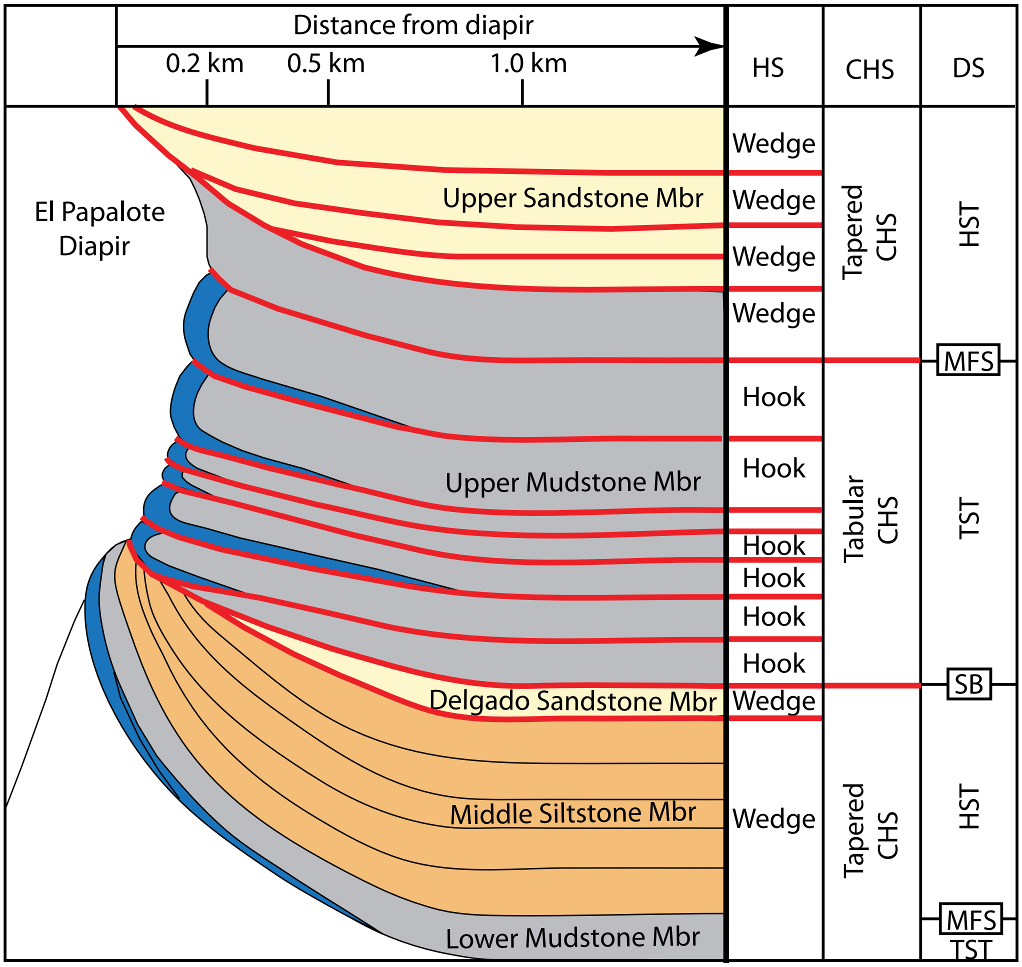

Fig. 7. Halokinetic (HS), composite halokinetic (CHS) and depositional sequence stratigraphy of the Upper Cretaceous through Lower Palaeogene stratigraphy exposed on the east side of El Papalote Diapir, La Popa Basin, Mexico. Colours and abbreviations as in Figure 6.

sediment-accumulation rates at this time were similar at the two locations. Second, the carbonates of the Aptian Cupido to Indidura formations formed part of a tapered CHS at La Popa Weld (Fig. 6), even though sediment-accumulation rate was presumably quite slow. We will address and explain these observations after discussing the controls on composite halokinetic sequence development in a later section.

Tabular composite halokinetic sequences primarily formed in the transgressive systems tract in the shallow-water setting of La Popa basin, when siliciclastic sediment influx to the shelf decreased due to shoreline transgression. The prime examples are the Lower Mudstone Member of the Potrerillos Formation at La Popa Weld and the Upper Mudstone Member at El Papalote Diapir (Figs 6 & 7). Again, however, the Middle Siltstone Member at La Popa

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Fig. 6. Halokinetic (HS), composite halokinetic (CHS) and depositional sequence stratigraphy of the Lower Cretaceous through Lower Palaeogene stratigraphy exposed on the north side of La Popa Weld, La Popa Basin, Mexico. Colours indicate dominant lithology of the unit: dark blue, carbonate lentil; light blue, regional carbonate unit; grey, outer-shelf mudstone; brown, prodeltaic shale; orange, lower-shoreface to middle-shelf siltstone; yellow, deltaic sandstone. LST: lowstand systems tract; TST: transgressive systems tract; HST: highstand systems tract; SB: sequence boundary; TS: transgressive surface; MFS: maximum flooding surface.

Weld also forms a tabular CHS despite regression and increased sedimentation rates.

Inflation of the diapirs into shallow and clear waters during deposition of the mudstone members of the Potrerillos Formation created an ideal environment for locally high rates of carbonate production and accumulation. Carbonate facies in hook halokinetic sequences in the mudstone members at La Popa Weld are significantly thicker and more extensive than those developed in the Middle Siltstone Member, which represents the early part of the highstand systems tract and higher detrital sediment influx into the basin (Figs 4 & 6). Higher carbonate production rates in the Lower Mudstone Member relative to the Middle Siltstone Member generated a slightly thicker sedimentary cover over the diapir and thus a slightly broader zone of drape folding, albeit still within the hook halokinetic-sequence framework. This difference in width permits identification of composite sequence boundaries between the stacked tabular CHS of the Lower Mudstone, Middle Siltstone and Upper Mudstone members (Fig. 6). In the Upper Mudstone Member at La Popa Weld we interpret a composite sequence boundary between La Popa lentils 3 and 4, whereby there is a shift from tabular CHS to tapered CHS. This is unusual for the transgressive systems tract, and we infer that it reflects a substantial increase in local carbonate grainstone production. At both La Popa Weld and El Gordo Diapir these grain-rich sediments form seismic-scale clinoforms up to 100 m high (Giles & Goldhammer 2000) that prograde off the diapir as much as 4 km into the adjacent minibasins (Giles *et al.* 2008).

Composite halokinetic-sequence boundaries in shelf settings have consistent locations within the stratigraphy. The major unconformities that mark upwards transitions from tapered to tabular CHS correspond to the beginning or early part of third-order transgressive systems tracts, whereas the upper boundaries of tabular CHS fall within the latest transgressive systems tract to earliest highstand systems tract (essentially near maximum flooding surfaces). This pattern is observed in La Popa Basin (Figs 6 & 7) and also in the Flinders Ranges of South Australia, where Kernen *et al.* (2012) document a tapered CHS with a lower composite halokinetic-sequence boundary just above a maximum flooding surface and an upper boundary at the beginning of the next transgressive systems tract.

Deep-marine slope and basinal settings (examples from the deepwater Gulf of Mexico)

Evaluation of halokinetic sequences in deepwater depositional environments is made more difficult by the virtual lack of appropriate field exposures, forcing us to rely on subsurface data. Seismic and well data document the existence of unconformity-bound folded sequences on the flanks of diapirs that were growing in slope or abyssal-plain settings. Published examples include the northern Gulf of Mexico onshore and offshore (e.g. Johnson & Bredeson 1971; Rowan *et al.* 2003) and the central North Sea (e.g. Davison *et al.* 2000). We have seen many unpublished examples from both basins, as well as from the offshore salt basins of Brazil, the Lower Congo Basin of West Africa and the Scotian Margin of Eastern Canada.

The seismic profile in Figure 8 from the deepwater northern Gulf of Mexico displays geometric features essentially identical to those seen in La Popa Basin. The secondary diapir, growing above an allochthonous salt canopy, is roughly vertical. The diapir edge has cusps, some more prominent and others more subtle, where local unconformities intersect the diapir. The unconformities delineate a series of composite halokinetic sequences in Plio-Pleistocene strata. Most are tapered CHS, with thinning and upturn occurring over a distance of 1 km in deeper sequences to 500 m in shallower sequences. Axial traces of drape-fold monoclines are inclined toward the diapir and 'jump' abruptly inboard at composite halokinetic-sequence boundaries (Fig. 8b). Within the tapered CHS are variable onlap and thinning geometries. Interspersed between the tapered CHS are two (and possibly three) tabular CHS, with most strata showing no thinning. The stack of tabular CHS are associated with slight flaring of the near-vertical diapir, suggesting diapir rise rates that are outpacing sediment-accumulation rates (Jackson *et al.* 1994).

The diapir in Figure 8 is vertical with symmetric topographic relief. However, many diapirs on the slope lean basinward and have asymmetric topographic relief with banked-in sediment on the updip, proximal flank and a steeper scarp on the downdip, distal flank (Fig. 9). This leads to observed differences in halokinetic deformation on the two flanks, as seen for the leaning diapir of Figure 10. Strata on the proximal (landward) side, where the salt–sediment interface dips away from the diapir, are only gently folded and minor truncations (although not shown on Figure 10) can be seen on seismic data. In contrast, strata on the distal (basinward) side beneath the flaring salt overhang are folded to vertical and truncated beneath unconformities. We would suggest that beds might actually go beyond vertical and that the degree of angular truncation might be even greater than shown.

Our outcrop observations from La Popa basin suggest that composite halokinetic sequence boundaries in shelf settings develop during or after prolonged periods of slow deposition and the consequent build-up of topographic relief over the

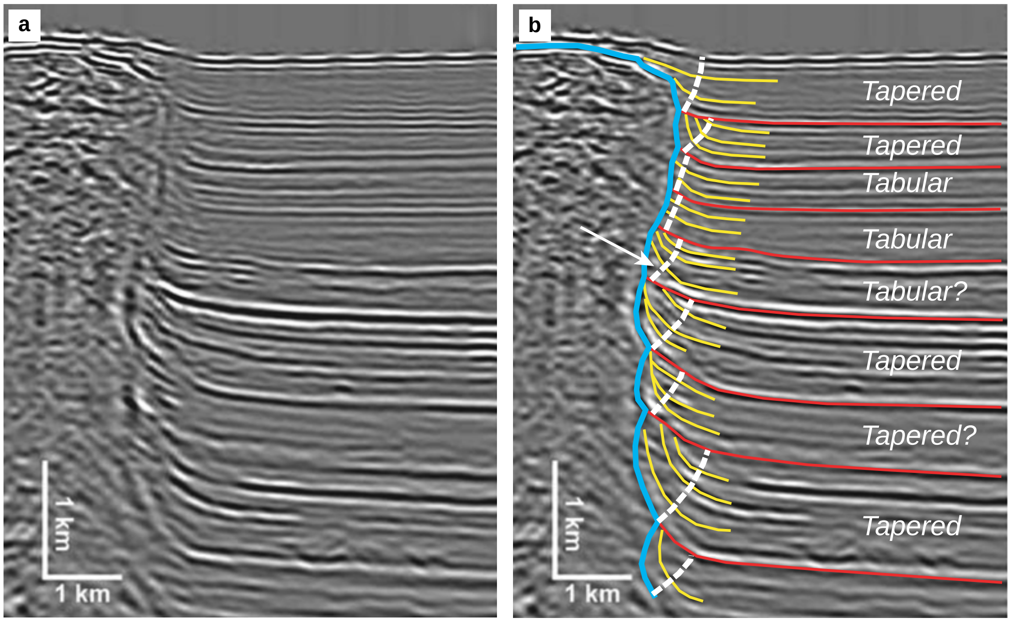

Fig. 8. Prestack depth-migrated seismic profile (reverse-time-migration sediment flood) of a secondary diapir and flanking strata from the northern Gulf of Mexico: (**a**) uninterpreted and (**b**) interpreted. The diapir edge is cuspate and stacked unconformities (red) define variably folded sequences identified as tapered or tabular CHS. White dashed lines are axial traces of halokinetic folds and the white arrow indicates a wedge-shaped body tentatively identified as a mass-wasting deposit. Vertical exaggeration 1.5:1. Seismic data courtesy of C. Fiduk and CGGVeritas.

Fig. 9. Dip-azimuth image of seafloor over Mica salt body in Mississippi Canyon, northern Gulf of Mexico (MTC: mass-transport complex). Illumination is from upper right such that NE-facing slopes are lighter and SW-facing slopes are darker. Seismic data owned by TGS, image courtesy of E. Mozer and Samson Offshore.

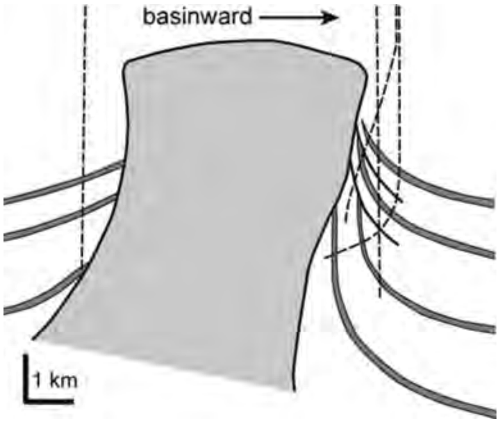

Fig. 10. Well-based cross-section of a diapir from the Louisiana shelf, northern Gulf of Mexico. The diapir is asymmetric, leaning basin-ward and the halokinetic geometries are correspondingly asymmetric. Thinning and folding is minor on the updip flank, whereas the basinward flank has stacked local unconformities and significant upturn and thinning of strata. No vertical exaggeration. Section courtesy of Apache Corp.

diapir leading to scarp failure and erosion. We draw the same conclusion from observations in deepwater settings. The deepwater unconformities interpreted in Figure 8b generally correlate with bright, continuous pairs of amplitudes within the minibasin that have been shown in other northern Gulf of Mexico minibasins to represent condensed hemipelagic mud deposited between third-order lowstand systems tracts (e.g. Prather *et al.* 1998; Weimer *et al.* 1998). In Figure 9 there are a series of slump scars along the topographic scarp and what are interpreted to be mass-wasting deposits at the toe of the scarp, indicating that current topographic relief has built up enough to cause scarp failure. This is happening today, which is a relative highstand in sea level with low sediment-accumulation rates in slope and basinal settings. On the seismic example, one wedge-shaped unit interpreted as a mass-wasting deposit (Figure 8b, white arrow) occurs just above a composite halokinetic-sequence boundary. Others may be present but below seismic resolution.

Erosional truncation, and thus halokinetic unconformities, may be generated in several ways in deepwater settings. First, scarp failure may cut into underlying strata folded over the diapir edge (Fig. 9). Second, turbidity currents flowing over diapirs accelerate down the steeper scarps on the basinward sides and may therefore become erosive (e.g. Kneller & McCaffrey 1995). Third, vigorous bottom currents from flowing oceanic masses are well documented in deep-marine (300–2000 m water depths) slope settings including the Gulf of Mexico (Howe *et al.* 2001; Stowe *et al.* 2002), and several studies have documented that rough sea-bottom topography accelerates flow rates and disturbs contourite flow making them highly erosional (Marani *et al.* 1993; Boldreel *et al.* 1998; Stowe *et al.* 2002). Of these three possible mechanisms, the first and third are expected to be most active during times of maximum topographic relief (i.e. slower sediment-accumulation rates), so that the unconformities would coincide with the hemipelagic condensed sections as interpreted in Figure 8. We therefore infer that deepwater erosional unconformities over slope diapirs and consequently composite halokinetic-sequence boundaries, are cut by some combination of local scarp failure and regional bottom currents.

Sub-aerial settings (examples from the Paradox and La Popa basins)

Halokinetic growth strata are also known from numerous sub-aerial depositional environments. Examples include the Pricaspian Basin of Kazahkstan (Rowan *et al.* 2003), the Fars Province of the Zagros Mountains (Jahani *et al.* 2007), the Paradox Basin (Trudgill 2011), La Popa Basin (Andrie *et al.* 2012), Cape Breton Island in Nova Scotia (Alsop *et al.* 2000) and the Basque Pyrenees of Spain (J. A. Muñoz pers. comm. 2009). The key difference between submarine settings and sub-aerial settings is that there is no hemipelagic deposition on top of the diapir in the latter; that the roof, if present, consists entirely of onlapping and overlapping minibasin fill and any remnant strata from earlier submarine phases of diapiric rise.

An example is the Onion Creek Diapir in the Paradox Basin of Utah, where flanking strata are dominated by alluvial to fluvial arkosic sandstones and conglomerates of the Permian Cutler Formation. The diapir at Cutler time was *c.* 3 km tall and there was no concurrent shortening (Trudgill 2011). The dominance of coarse-grained material and the relative paucity of interbedded mudstones (Condon 1997) suggest relatively rapid sediment-accumulation rates. Strata thin and fold to beyond vertical in a zone *c.* 1 km wide, several low-angle unconformities ($<20^\circ$) occur within 100 m of the diapir and reworked clasts of the evaporite unit are locally found adjacent to the diapir (Trudgill 2011). In other words, the Cutler Formation forms a tapered CHS.

In La Popa Basin, the youngest stratigraphic interval (Palaeogene Carroza Formation) constitutes fluvial red beds with approximately equal proportions of fine-grained sandstone and mudstone-siltstone (Buck *et al.* 2010). The diapir was *c.* 6 km tall at the time and was being squeezed during the Hidalgoan Orogeny (Rowan *et al.* 2012). Strata of the Carroza Formation are thinned and folded in a zone that narrows upwards from over 1 km wide to less than 100 m wide, have rare unconformities with angular truncation less than 20° and contain occasional mass-wasting deposits with diapir-derived detritus and clasts of the underlying Viento Formation that was presumably draped over the edge of the diapir (Andrie *et al.* 2012). The Carroza and Viento formations together form a large tapered CHS. However, the halokinetic geometry in the upper part of the Carroza is in some ways transitional between the tapered and tabular CHS end-member styles proposed here, because the strata form wedge sequences but all folding is within a narrow zone more typical of hook sequences. We offer a possible origin of this transitional geometry in a later section.

Sequence-bounding halokinetic unconformities are relatively rare in both the Carroza Formation and the Cutler Formation in the Paradox Basin. We suggest that this may be a common theme in non-marine settings because of the types of possible erosional processes in this environment. Erosion may be caused by fluvial channel incision over the

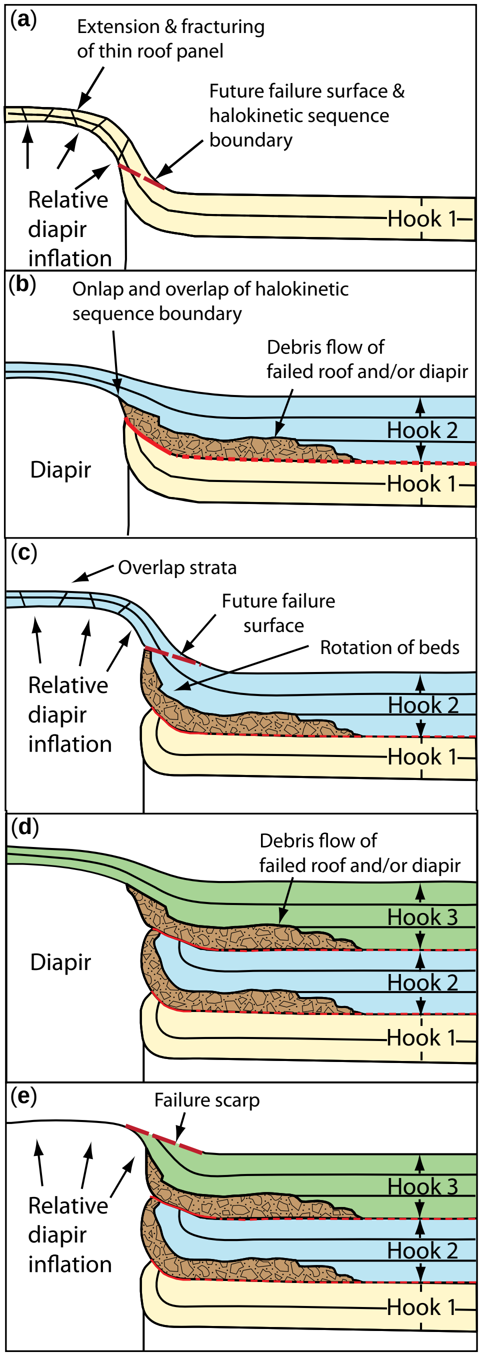

Fig. 11. Genetic model for formation of tabular CHS: (**a**) inflated diapir with folded thin roof (Hook 1); (**b**) failure of roof forming unconformity overlain by debris flow (brown) and onlap/overlap of diapir (Hook 2, blue); (**c**) relative diapir inflation and drape folding of Hooks 1 and 2; (**d**) failure of roof panel with onlap/overlap forming Hook 3; (**e**) failure of Hook 3 roof panel.

diapir, gravitational mass wasting and potentially aeolian processes, all of which will be of local extent. More generally, non-marine halokinetic growth strata deposit, rotate and erode almost on a bed-by-bed basis and thus commonly show progressive dip rotations and onlap relationships but not well-defined angular unconformities that truncate several beds.

Composite halokinetic-sequence models

The external geometry, internal character and facies distribution within halokinetic sequences is a function of the interplay between local sediment-accumulation rate and the rate of diapir rise (Giles & Lawton 2002; Rowan *et al.* 2003). Based on our observations in the various depositional settings described above, the same is true of composite halokinetic sequences. Sediment-accumulation rate is largely controlled by the flux of sediment to the site, local erosion and accommodation space. These are in turn influenced by external factors such as eustatic sea-level changes, tectonics and climate, and local factors such as the salt-related geometry of sediment-transport pathways and depocentres (Rowan & Weimer 1998). Diapir-rise rate, which creates local accommodation, is controlled by the net differential load on the underlying salt layer (Vendeville *et al.* 1993) and any shortening (which increases diapir-rise rate; Vendeville & Nilsen 1995) or extension (which slows or even reverses diapir rise rate; Vendeville & Jackson 1992). The result of the interplay between sediment-accumulation rate and diapir-rise rate is topographic relief over the diapir that fluctuates over time in both height and width. Tabular and tapered CHS represent different manifestations of this process.

Diapir-rise rate, as used here, is a relative term. It does not necessarily mean the actual rate of salt rise up a passive diapir. Instead, it is the rate of diapir rise relative to minibasin subsidence (plus differential compaction over the rising diapir), that is, the net creation of local accommodation space. For example, consider a diapir flanked on one side by a basin with no underlying salt (and thus no local subsidence) and on the other by a minibasin that is actively subsiding into deep salt. The rise rate of salt in the diapir is the same, but the relative rise rate is higher when the minibasin is also sinking. In attributing the type of composite halokinetic sequence to the ratio between sediment-accumulation rate and diapir-rise rate, we are effectively taking the generation of local accommodation space out of the sediment-accumulation side of the equation, where it traditionally belongs, and placing it within diapir-rise rate. Our goal is not to address sediment-accumulation or diapir-rise rates *per se*, but to examine how the interplay between them influences near-diapir deformation and deposition.

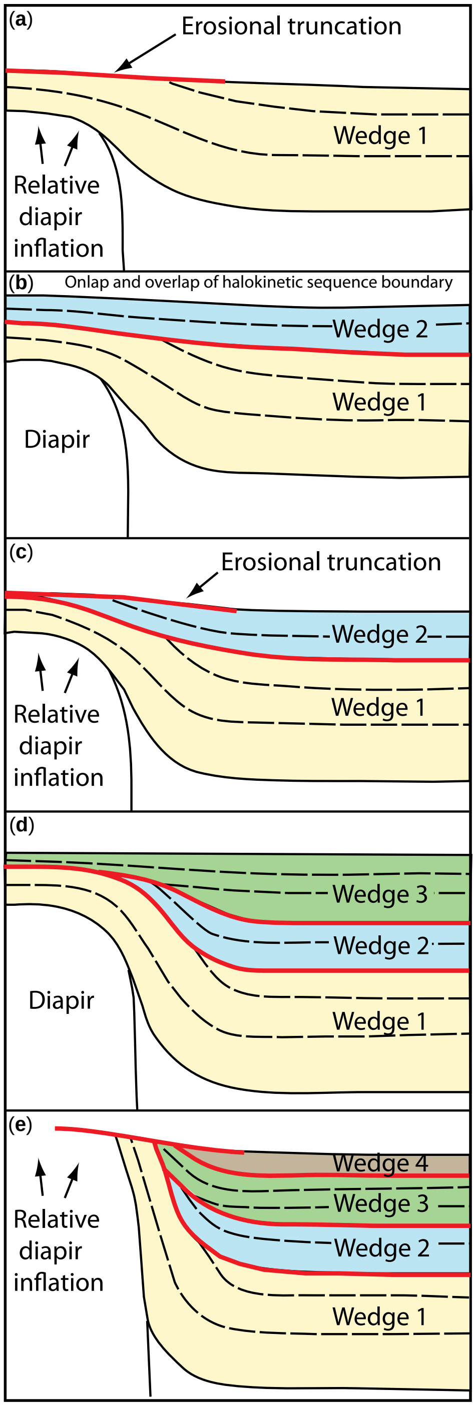

Fig. 12. Genetic model for formation of tapered CHS: (**a**) thick roof panel over diapir, which inflates resulting in erosional truncation of roof panel and Wedge 1; (**b**) overlap by Wedge 2; (**c**) erosional truncation of Wedge 2 over inflating diapir; (**d**) onlap and overlap of Wedge 3; and (**e**) erosional truncation of Wedge 3 and onlap of Wedge 4.

Tabular CHS form when overall sediment-accumulation rate adjacent to the diapir is less than diapir-rise rate over the timescale of a third-order depositional sequence. Within this larger-scale pattern are parasequence-set-scale fluctuations in sediment-accumulation rate that form individual hook halokinetic sequences. Because long-term diapir-rise rate outpaces sediment accumulation, topographic relief over the diapir increases, resulting in little deposition of sediment over the diapir and a correspondingly thin roof. With continued diapir inflation the roof panel folds over the diapir edge, with the width of the deformation narrow because of the thin roof (Fig. 11a). The roof strata on the steep unstable margins of the diapir (and even part of the diapir itself) are prone to failure and mass wasting, especially if the roof is extended and fractured during folding. The failure scarp or erosion of the roof creates an unconformity surface that has significant angular discordance adjacent to the diapir, with overlying mass-wasting deposits that run out and likely downlap onto the minibasin floor (Fig. 11b). Short-lived periods of more rapid deposition result in onlap and progressive overlap of any mass-wasting deposits and the diapir (Fig. 11b). Slower deposition leads to increased topographic relief, continued folding of the underlying sequence and drawback of beds beneath the unconformity to form greater angular discordance and a cusp (Fig. 11c). Onlapping and overlapping strata become the next roof panel to be drape folded, and repetition of the process creates the tabular CHS (Fig. 11d, e). Because the top of the diapir is periodically higher than the level of the minibasin floor, the outward push of salt against the free surface (as shown by the arrows within the salt in Fig. 11a) may enhance drape folding (Schultz-Ela 2003). In addition, because of the high depositional relief and narrow zone of deformation, abrupt depositional facies transitions near the diapir may be common.

Tapered CHS form when overall sediment-accumulation rate adjacent to the diapir exceeds diapir-rise rate over the timescale of a third-order depositional sequence. Parasequence-set-scale fluctuations in sediment-accumulation rate form the individual wedge halokinetic sequences. The overall more rapid sedimentation results in depositional overlap of the diapir, forming a relatively thick roof and a correspondingly wide zone of drape folding (Fig. 12a). Topographic relief is minor to non-existent because sedimentation keeps up with the local accommodation created by diapiric rise. With a relative decrease in sediment-accumulation rates the diapir continues to rise, creating an area of slight topographic relief that may become a zone of sedimentary bypass or erosion, thereby producing a low-angle truncation surface (Fig. 12a). Diapir-derived mass-wasting deposits are rare because of the generally low relief. The resumption of higher net sediment-accumulation rates results in onlap and progressive overlap of the low-angle unconformity and the diapir roof strata (Fig. 12b), with continued rotation of underlying wedges due to diapiric rise. The onlapping and overlapping strata form the next wedge (Fig. 12c), with repetition of the process creating the tapered CHS (Fig. 12d, e). Note that the deepest wedge is vertical in Figure 12e; the addition of another wedge will however continue the process so that the deepest wedge in the tapered CHS becomes overturned adjacent to the salt, effectively pushing into and displacing salt. There is little, if any, outward push of salt that could enhance drape folding (Schultz-Ela 2003) because the top of the diapir is rarely above the level of the minibasin floor. Also, because of the low depositional relief and broad zone of deformation, depositional facies transitions are few, cover wide areas and are gradual.

In our model all folding is near-surface and drape-fold geometries become locked in at depth (Rowan *et al.* 2003). The toe of the drape-fold scarp is the lower hinge of a monoclinal fold (Fig. 13). The axial trace of this fold intersects the diapir, forming a downward-tapering triangle of deformation with no further folding outside this triangle. The depth at which deformation ceases is a function of two variables: first, the steepness of the salt–sediment interface so that deformation does not extend as deep if the diapir narrows upward; and second, the width of the drape fold and thus the thickness of the roof. Consequently, hook halokinetic sequences and tabular CHS have only a minor effect on underlying sequences, whereas folding of wedge halokinetic sequences and tapered CHS causes significant folding of deeper strata. It is this process that causes truncated beds to draw back along the halokinetic unconformities and produce cusps at the salt–sediment interface (Rowan *et al.* 2003).

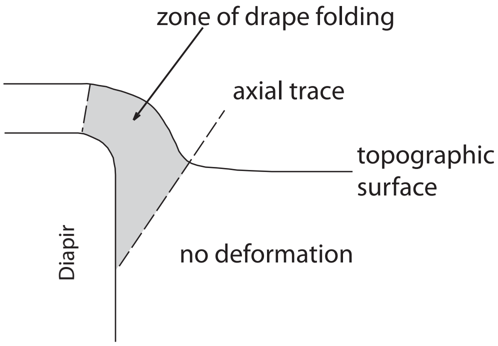

Fig. 13. Area of drape-fold deformation at any given time is governed by surface topography relative to diapir geometry.

Composite halokinetic sequences can be stacked to produce four distinctive patterns. When the higher composite sequence is a tabular CHS, there is little drape-fold impact on the lower sequence. Thus, the geometric boundary formed when two tabular CHS are stacked may be only a subtle jump in the trend of the zone of stacked drape-fold axial traces (Fig. 14a). The geometry is also simple when a tabular CHS overlies a tapered CHS, with a significant jump in fold hinge zones at the boundary (Fig. 14b). In contrast, a tapered CHS above another tapered CHS creates a more pronounced cusp, a more extensive angular unconformity and potentially overturned strata in the lower sequences because of the deeper extent of folding (Fig. 14c). Jumping fold-hinge zones between two tapered CHS are easily recognized because the youngest part of the axial trace of the underlying tapered CHS terminates more than 500 m from the diapir and the oldest part of the axial trace in the overlying tapered CHS jumps back to a point closer to the diapir (e.g. Fig. 8). Finally, a tapered CHS above a tabular CHS deforms the deeper sequence, also forming a pronounced cusp, extensive unconformity and overturned beds (Fig. 14d). It may appear superficially that the deeper sequence is also a tapered CHS because of the wide zone of deformation, but the broader folding was superimposed upon the tabular CHS after its formation and strata within the tabular CHS are parallel until very close to the diapir.

Our model predicts that diapir-derived mass-wasting deposits should occur during or after prolonged periods of slow sedimentation relative to diapir inflation. They are therefore most likely at the bases of hook halokinetic sequences and at the bases of both tabular and tapered CHS, but less likely within tapered CHS. Mass-wasting deposits are expected just above or below the halokinetic sequence boundaries.

Discussion

We have presented examples of halokinetic growth strata from different salt basins and depositional

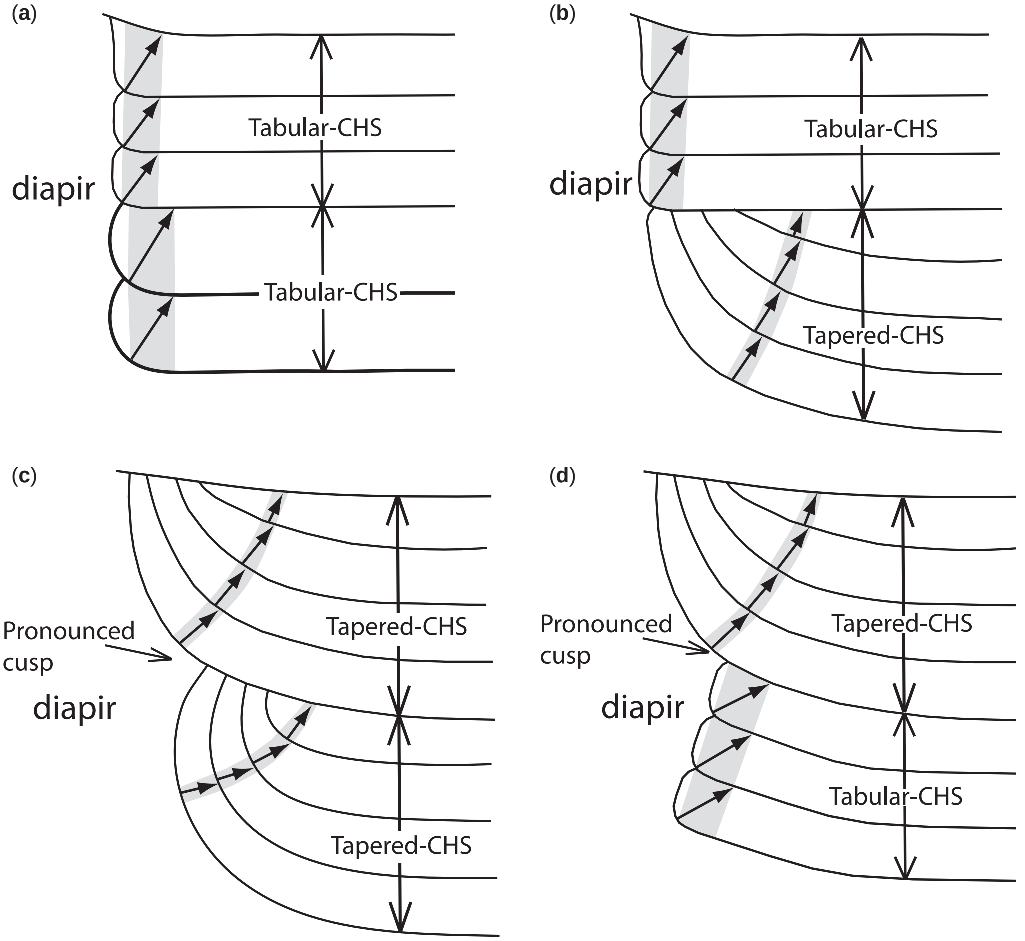

Fig. 14. Geometric patterns of stacked composite halokinetic sequences (CHS): (**a**) tabular CHS over tabular CHS; (**b**) tabular CHS over tapered CHS; (**c**) tapered CHS over tapered CHS; and (**d**) tapered CHS over tabular CHS.

settings and derived genetic models for halokinetic folding adjacent to steep diapirs based on those examples. In the following sections, we discuss several aspects of salt-related deformation and deposition: (1) the interplay between sediment-accumulation and diapir-rise rates in controlling the development of composite halokinetic sequences; (2) broader zones of folding and thinning of mini-basin strata; (3) the presence or absence of halokinetic sequences beneath allochthonous salt; and (4) the implications of our models for hydrocarbon exploration and production in diapir-flanking traps.

Composite halokinetic sequences

Halokinetic sequences and composite halokinetic sequences, as defined earlier (Giles & Lawton 2002; Rowan *et al.* 2003) and in this paper, are applicable only to near-diapir strata. Folding and thinning in hooks and tabular CHS take place within 200 m of the diapir, whereas they occur up to 1 km from the diapir in wedges and tapered CHS. The deformation and associated impact on deposition is entirely related to the height and extent of local topographic relief over passive diapirs, which are in turn controlled by the interplay between sediment-accumulation rate and diapir-rise rate.

La Popa Basin offers excellent opportunities for examining controls on composite halokinetic-sequence development. The composite halokinetic-sequence types for each stratigraphic unit at El Papalote Diapir and La Popa Weld are listed in Table 1, along with inferred qualitative sediment-accumulation rates and salt-rise rates. The former

Table 1. *Composite halokinetic sequence types documented at La Popa weld (Weld) and El Papalote (El Pap) diapir in La Popa Basin, Mexico and interpreted relative rates of salt rise and sediment accumulation at both diapirs for various stratigraphic units*

Stratigraphic unit	Sediment-accumulation rate	Salt-rise rate		Composite halokinetic-sequence type	
		Weld	El Pap	Weld	El Pap
Carroza	Moderate	Fast		Tapered	
Viento	Fast	Fast		Tapered	
Upper Sandstone	Fast		Moderate		Tapered
Upper Mudstone	Slow	Fast	Moderate	Tabular	Tabular
Middle Siltstone	Moderate	Fast	Moderate	Tabular	Tapered
Low. Silt.-Low. Mud.	Slow	Moderate		Tabular	
Parras-Muerto	Mod-fast	Moderate		Tapered	
Cupido-Indidura	Slow	Slow		Tapered	

are simply a function of lithology and interpreted depositional environment with, for example, deltaic or shoreface sandstones assumed to represent rapid deposition and outer-shelf shales assumed to represent slow deposition. Salt-rise rate is inferred to have gradually accelerated over time as growing minibasins increased the differential load on the deep salt layer. In addition, shortening-induced squeezing of diapirs, which began early during the deposition of the Middle Siltstone Member of the Potrerillos Formation, would have increased salt-rise rates. However, this varied between the two diapirs: shortening was significant at La Popa Weld (Rowan *et al.* 2012) but only minor at El Papalote Diapir (Rowan *et al.* 2003).

As described earlier units with rapid sediment-accumulation rates, such as the Parras–Muerto succession and the Upper Sandstone Member of the Potrerillos Formation, formed tapered CHS (Figs 6 & 7, Table 1). Sediment-accumulation rate generally outpaced diapir-rise rate, developing relatively thick roofs, wide zones of drape folding and minimal topographic relief. In contrast, units with slow sediment-accumulation rate (such as the mudstone members of the Potrerillos Formation) formed tabular CHS (Figs 6 & 7, Table 1) where diapir-rise rate outpaced sediment-accumulation rate, resulting in thin roofs, narrow zones of drape folding, significant topographic relief and common mass wasting. However, the Cupido through Indidura formations, comprising mostly carbonate mudstone, calcareous shale and cherty shale (Lawton *et al.* 2001) and thus presumably representing slow deposition, formed a tapered CHS (Fig. 6, Table 1). We suggest that diapir-rise rate was also slow because the minibasin was thinner at the time, so that differential pressure on the deep salt was lower, and because there was no shortening. Even though sediment-accumulation rate was slow, it was therefore able to keep up with diapir-rise rate, generating a thicker roof and broader zone of halokinetic deformation. This relationship highlights the importance of the relative rates of diapir rise and sediment accumulation, not absolute rates, in forming composite sequence types.

The Middle Siltstone Member of the Potrerillos Formation represents deposition during the highstand systems tract when detrital influx had increased relative to the underlying Lower Mudstone Member, and thus might be expected to have formed tapered CHS. This is indeed what is observed at El Papalote Diapir (Fig. 7, Table 1). However, the Middle Siltstone Member at La Popa Weld (Fig. 4) has well-developed hook halokinetic sequences forming several tabular CHS (Fig. 6, Table 1). Assuming that sediment-accumulation rates at this time were roughly the same across the shelf (the thicknesses of the unit are similar in both locations), variations in diapir-rise rate between the diapirs may have caused the differences in halokinetic-sequence style. At this time, Hidalgoan shortening had just begun which would have squeezed the La Popa salt wall (Rowan *et al.* 2012), increasing diapir-rise rate to the point that it outpaced sediment-accumulation rate and formed tabular CHS. El Papalote Diapir experienced only insignificant shortening (Rowan *et al.* 2003), so that diapir-rise rate was lower and a tapered CHS formed instead. Again, it is the relative rates that are important in forming composite halokinetic sequences.

Variations in near-diapir deformation from deeper to shallower levels tend to follow a common pattern in submarine depositional environments, with deeper tapered CHS transitioning upward to tabular CHS. We suggest that this progression results from changes in the differential sediment load driving salt flow from the underlying salt level, assuming that average third-order sediment-accumulation rates stay relatively constant over time. In earlier stages there is a smaller differential sediment load driving salt flow so that even relatively low sediment-accumulation rates will outpace diapir-rise rates, resulting in tapered CHS. As differential pressure on the underlying salt increases due to minibasin thickening, diapir-rise rate is more rapid so that tabular CHS tend to become dominant. Of course, significant third-order variations in sediment-accumulation rate will alter this pattern. Additionally, shortening of diapirs at any time increases diapir-rise rates so that tabular CHS are more likely, and any extension has the opposite effect.

We described earlier how the fluvial Carroza Formation at La Popa Weld forms a tapered CHS that narrows upwards significantly, to the point that all folding at shallow levels is within 100 m. We infer that sediment-accumulation rate was consistently rapid enough so that wedges formed rather than hooks, but that overall rapid diapir rise resulted in gradual unroofing and sub-aerial exposure of the diapir. As the roof thinned the zone of topographic relief narrowed, producing halokinetic deformation that decreased in width upwards and a growth axial trace that converged upwards with the diapir (Fig. 15). A similar scenario is possible in submarine environments if the diapir roof is thinned, even in cases of a high ratio of sediment-accumulation rate to salt-rise rate, by flow-stripping or canyon incision (e.g. Lee *et al.* 1996). In such cases, a wide tapered CHS will transition upwards to an abnormally narrow zone of wedge halokinetic sequences.

We stress that the models presented here are end members. Intermediate or transitional styles exist, as exemplified by the Carroza Formation in La Popa Basin (Fig. 15) and several of the sequences in Figure 8. Nevertheless, our experience suggests that the simple models of composite halokinetic sequences presented here sufficiently explain the vast majority of observed geometries in different salt basins. Natural variations in the interplay between sediment-accumulation rate and diapir-rise rate at the parasequence-set scale will result in a wide variety of possible stratal-convergence, onlap, overlap and offlap patterns within composite halokinetic sequences.

Minibasin-scale folding and thinning

Folding and thinning of strata can, of course, be observed over broader zones than those defined for composite halokinetic sequences. Rowan *et al.* (2003) demonstrated that squeezed diapirs from both La Popa Basin and the northern Gulf of Mexico have halokinetic geometries different from those of diapirs with little or no shortening. The zone of folding and thinning is up to 3 km wide, but stratal dips are generally not as steep and angular discordance at halokinetic unconformities is generally less severe because of broader topographic highs. Some portion of this deformation is caused by the topographic relief generated by growing folds that intersect the diapirs rather than by the diapirs themselves, so it is unclear how much is strictly halokinetic as defined here. In any case, gentle folding and angular truncation apply only to the upper portions of diapirs with minor to moderate amounts of shortening. Greater shortening and any thrusting can lead to steeper dips, especially of older, deeper stratigraphic units.

Broad areas of differential folding and thinning are even more common due to differential subsidence of minibasins into the underlying salt layer. Withdrawal/and/or inflation of salt creates variable geometries such as simple synclinal minibasins, turtle structures, half-turtles and expulsion rollover structures. Depocentres may be centrally located in the minibasin, in which case strata thin towards the diapir over a wide area. Thinning may be manifested by any combination of simple convergence of beds, onlap and erosional truncation. Alternatively, depocentres may be peripheral (also called rim synclines) with the thickest strata adjacent to the diapir, in which case only local halokinetic folding occurs.

Diapirs tend to evolve over time from broad, low-relief areas of inflated salt to narrower, taller diapirs. Thus, minibasin-scale folding and thinning typically characterize the older, deeper portions of minibasins. Gradual wedging of the Cupido-Indidura interval at La Popa Weld (Fig. 6) may reflect this type of deep, minibasin-scale deformation. In contrast, local halokinetic deformation is dominant adjacent to the shallower, vertical to flaring parts of diapirs. However, wider areas of folding at shallow levels may again be caused by shortening of diapirs and minibasin flanks.

One (or, more rarely, both) sides of diapirs may have older strata that are draped along the diapir flank for a considerable vertical distance with steep (up to vertical or even overturned) dips. Strata in these ‘megaflaps’, which may be constant thickness or thin towards the diapir, are onlapped by growth wedges of younger minibasin fill. An exposed example from a shallow-water setting is illustrated in Figure 16, where strata deposited directly after deposition of the salt layer are rotated up to 4 km above their level in the minibasin. The megaflap thins upwards through a combination of stratal convergence and minor onlapping onto the edge of the diapir. A subsurface example from the northern Gulf of Mexico displays a similar geometry (Fig. 17), with strata just above an allochthonous salt sheet forming a megaflap whose top is over 5 km above its minibasin level. The megaflap is conformable to the top/edge of salt, is onlapped by younger minibasin strata and is erosionally

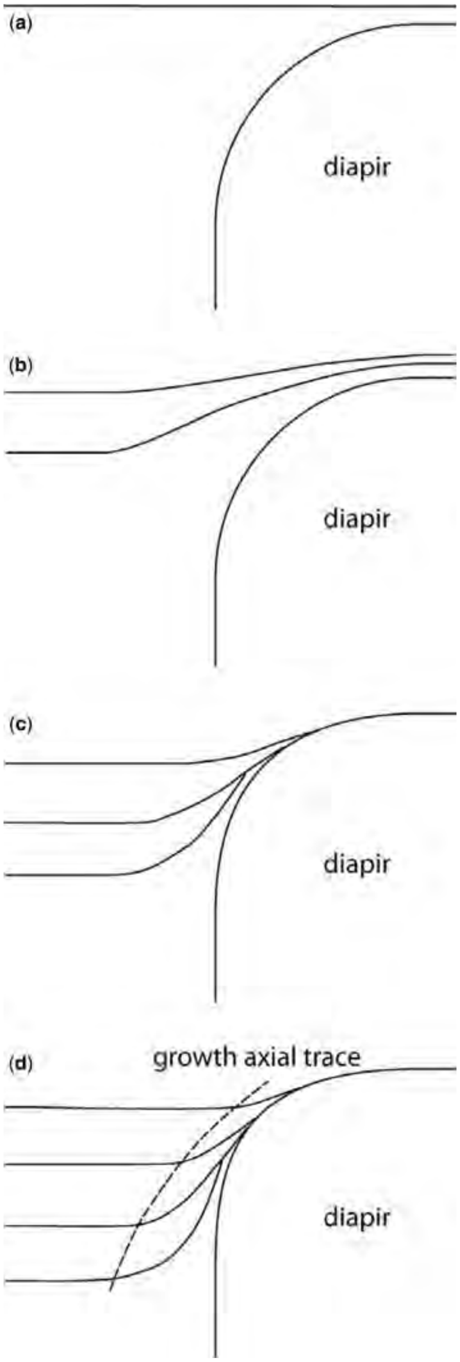

Fig. 15. Model for development of upwards-narrowing halokinetic deformation in sub-aerial environments: (**a**) buried diapir with no topographic relief; (**b**) topographic relief increases during relatively rapid salt rise; (**c**) diapir becomes unroofed through drape folding of overburden, erosion and/or slump failure, thereby thinning the onlapping wedge; and (**d**) minor onlap of exposed diapir.

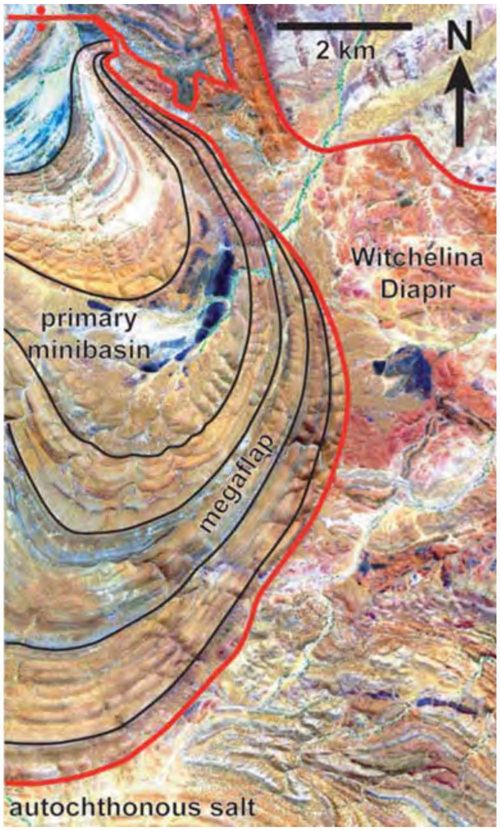

Fig. 16. Hyperspectral image of the Witchelina Diapir in the Willouran Ranges of South Australia. Regional structural attitudes make the plan-view pattern essentially a distorted cross-section. The autochthonous Neoproterozoic Callanna evaporite is at the bottom-left of the image, underlying a primary minibasin that borders the diapir (outlined in red). Strata progressively thin towards and onlap the edge of the diapir, forming a large upturned megaflap along the diapir flank. The interpretation at the upper left, including breakout of the salt into a welded canopy, is taken from Hannah (2009).

truncated at its crest. Equivalent geometries are well known from drilling results in the subsalt domain of the northern Gulf of Mexico, where anomalously old and steep strata have been penetrated at shallow levels adjacent to diapiric feeders to the overlying canopy.

We envision two possible origins for megaflaps. First, they may form as a result of shortening, with one minibasin thrust over the other as the diapir narrows and possibly welds out (e.g. Rowan & Vendeville 2006). Alternatively, if there is little demonstrable shortening (as is the case for both the examples depicted in Figs 16 and 17), a megaflap represents the mostly conformable overburden of a laterally extensive salt body (autochthonous or allochthonous) with a subhorizontal top. The upwards transition from parallel or slightly thinning strata of the megaflap to more pronounced thinning and onlap (e.g. orange horizon in Fig. 17) probably highlights when salt broke through its structurally conformable cover and began either primary or secondary diapirism and associated minibasin growth. In Figure 16, the stratal geometries show that the salt–sediment interface gradually steepened over time as the minibasin sank and the salt inflated. Although it appears that the salt was diapiric because of the minor truncation of minibasin strata at the edge of the diapir, the very shallow water depth of the minibasin fill suggests that the salt was sub-aerially exposed and simply progressively onlapped.

In the case of allochthonous salt, megaflaps are effectively equivalent to one typical manifestation of carapace. Carapace is defined as condensed, subparallel strata deposited on bathymetric highs over canopies or sheets (Hart *et al.* 2004). Carapace may be preserved as steeply dipping strata at the edge of a secondary minibasin. In other words, the megaflap in Figure 17 is identical to carapace. Similarly, megaflaps that comprise dominantly mud may be termed shale sheath. Shale sheath also consists of condensed mud that was deposited over salt but ends up draping the flank of a diapir (Johnson & Bredeson 1971). Shale sheath may have the scale of a megaflap, representing the deepest strata of a minibasin, or it may be smaller-scale as part of a composite halokinetic sequence. Despite the overlapping and potentially confusing terminology, we adopt the term megaflap because it describes only the geometry, regardless of lithology or whether it flanks primary or secondary diapirs.

Allochthonous salt

Allochthonous salt sheets may have associated halokinetic folding similar to that on steeper diapirs. Kernen *et al.* (2012) document a tapered CHS approximately 900 m thick beneath a base-salt ramp of the Patawarta salt sheet in the Flinders Ranges of South Australia, with strata progressively steepened and ultimately overturned over a distance of *c.* 1 km. A similar geometry was shown on prestack depth-migrated seismic data from the deepwater northern Gulf of Mexico by Rowan *et al.* (2010). However, the Patawarta salt sheet also has undeformed subsalt strata at higher stratigraphic levels that truncate against the base salt without any halokinetic folding; similar features are known from the northern Gulf of Mexico (Rowan *et al.* 2010). Allochthonous salt typically advances on a thrust fault that links the toe of the salt to the sea floor (Rowan *et al.* 2003, 2010; Hudec & Jackson 2006, 2009). The thrust becomes the base of the salt sheet and if the thrust emerges at the toe of the topographic scarp (boundary of zone of drape folding, Fig. 13), only undeformed strata are preserved in the footwall and hence beneath the salt (Rowan *et al.* 2003).

Rowan *et al.* (2010) suggested that the primary factor in controlling subsalt deformation is the interplay between sediment-accumulation rate and the rate of lateral salt supply to the toe of the sheet. When the ratio is high, thrust advance is pinned and the salt sheet inflates (Hudec & Jackson 2009), creating a tapered CHS before breakthrough and further thrust advance. When the ratio is low, the salt advances on a thrust that emerges at the toe of the scarp so that there is no halokinetic folding. Since an equivalent low ratio of sediment-accumulation rate to diapir-rise rate creates tabular CHS in steeper diapirs, it may be that tabular CHS are rare to absent beneath allochthonous salt. The folded strata are in the hanging wall of the thrust and simply get carried along and possibly slumped off.

Brief local extrusion of allochthonous salt may periodically occur, forming salt wings (*sensu* Diegel *et al.* 1995) adjacent to steeper diapirs. This is likely to happen during times of slow sediment-accumulation relative to diapir rise, when topographic relief is at a maximum. In other words, salt wings are expected to be found at the bases of hook halokinetic sequences and at composite halokinetic sequence boundaries, exactly where mass-wasting deposits are most common. Both are formed by failure of an unstable topographic high but with different rates: mass wasting occurs rapidly, whereas salt extrusion is the slower gravitational failure of salt and its roof. Differentiating between them on seismic data might be difficult, but the salt wings should ideally have a higher-amplitude top and overall higher velocities than mass-wasting deposits.

Implications for exploration/production

The models presented here have important implications for hydrocarbon exploration and development in diapir-flank traps, impacting many elements of the petroleum system. Trap geometries will of course be different in tapered and tabular CHS because of the varying widths of folded strata, the unequal degree of folding and the variable development of unconformities.

Halokinetic deformation also affects reservoir development. For example, the extent of lowstand turbidite sandstones in a deepwater tabular CHS should have no structurally controlled facies variations until within at most 100–200 m of the diapir. In contrast, sands in a tapered CHS will have variable relationships to the diapir. With a thick roof over the diapir at the beginning of a third-order lowstand in deepwater environments, the area of topographic relief is broad so that sands deposited early in the lowstand may onlap the scarp and pinch out more than 500 m from the diapir. If roof thickness and topography were reduced via erosion and slumping during the preceding highstand, sands may be deposited much closer to the diapir. In any case, because sediment-accumulation rate is high relative to salt-rise rate, subsequent sands will gradually onlap and potentially overlap the diapir roof so that some might even end up in contact with the salt after continued diapir rise. As sedimentation rate slows and the diapir develops greater topographic relief, sands may offlap the roof. The specific relationships will depend on the details of parasequence-set-scale variations in sedimentation rate. Once turbidite deposition decreases significantly because of rising sea level, increasing topographic relief will lead to scarp failure so that some stratigraphy within the tapered CHS may be truncated beneath the unconformity some distance from the diapir (see Fig. 10). In addition, turbidites deposited early in the overlying sequence will respond depositionally to the irregular sea bottom topography created by diapir-flank failure and associated mass-transport deposits. The response may be depositional diversion or bypass, onlap or infill of the irregular topography.

It is tempting to associate sand presence with tapered composite halokinetic sequences because these form when sediment-accumulation rate is rapid relative to diapir-rise rate. Indeed, the two or three tabular CHS in Figure 8 likely represent a time of slower, mud-prone deposition because no known contraction or extension has affected this diapir. However, diapir-rise rate can also change and thereby generate changes in halokinetic geometry. As the diapir and minibasin both grow, rise rate and subsidence rate will increase. Even if average sedimentation rates (and sand percentage) stay constant, there will be an upwards transition from tapered CHS to tabular CHS, a commonly observed pattern on deepwater diapirs. In addition, pulses of shortening will increase salt-rise rate, making tabular CHS more likely even if plenty of sand is

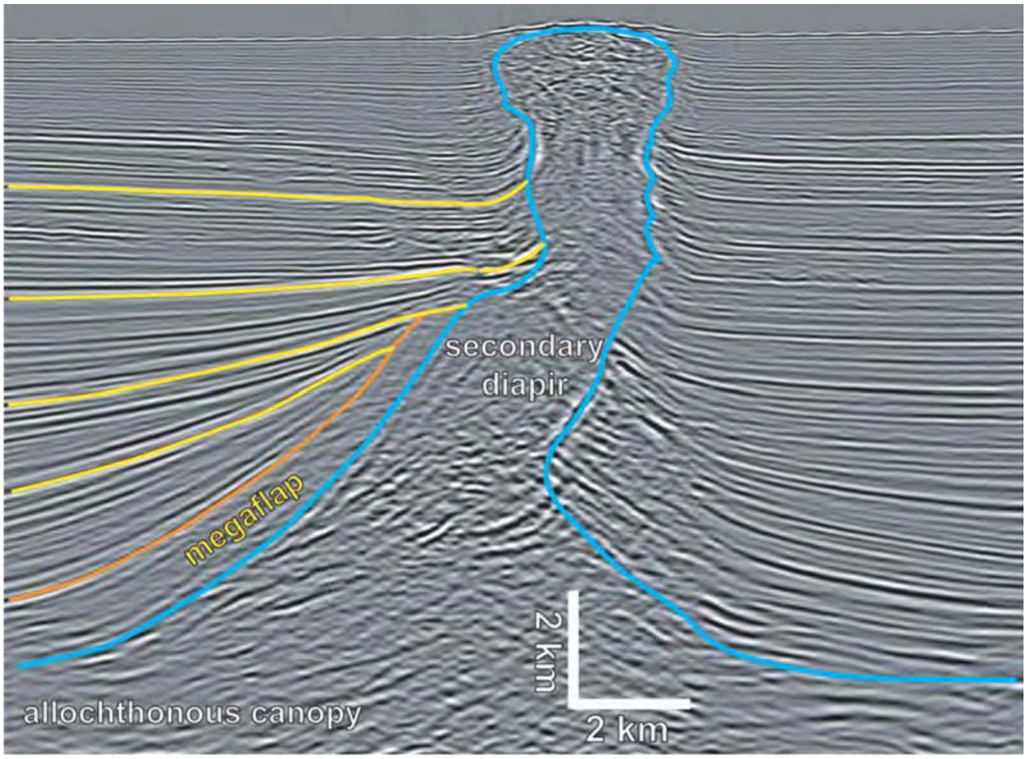

Fig. 17. Prestack depth-migrated seismic profile (reverse-time migration sediment flood) of the same diapir from the northern Gulf of Mexico illustrated in Figure 8. The left minibasin has a basal megaflap that is draped along the diapir flank and onlapped by a growth wedge of younger minibasin strata. Note the local halokinetic folding at higher levels of the diapir. No vertical exaggeration. Seismic data courtesy of C. Fiduk and CGGVeritas.

in the system. Any extension will have the opposite effect, with tapered CHS more common.

The variable distribution of reservoirs also impacts potential seal against salt or steep welds since some of the sands will be in contact with the salt/weld and others will be encased in shales some distance away. Moreover, sands at lower levels in tapered CHS will be steep such that pressures might be higher and only a small, local column can be contained, whereas higher sands in a tapered CHS might have lower pressure, larger column heights and greater lateral extent. Finally, the geometries might impact which sands see a hydrocarbon charge: if migration is only up along the salt–sediment interface, reservoirs isolated beyond a certain distance from the diapir might remain wet; if, in contrast, hydrocarbons migrate towards the diapir from more basinal positions, the isolated sands might make the best targets.

Conclusions

Strata flanking passive diapirs often thin towards the diapirs over large areas, especially at deeper stratigraphic levels, due to either differential subsidence of minibasins into underlying salt or regional shortening of the diapirs and minibasins. More restricted drape folding and stratal thinning is also common due to local topographic relief over the diapirs, creating unconformity-bound halokinetic sequences. In hook halokinetic sequences, folding occurs within 50–200 m of the diapir, angular discordance at the unconformities can approach 90°, mass-wasting deposits are common and facies changes near the diapir are abrupt. In wedge halokinetic sequences, the zone of deformation is 300–1000 m wide, angular truncation is typically less than 20°, mass-wasting deposits are less common and any facies changes are gradational over larger distances. Both hook and wedge halokinetic sequences have thicknesses and timescales matching those of depositional parasequence sets.

Halokinetic sequences stack into composite halokinetic sequences. Multiple hook halokinetic sequences form tabular composite halokinetic sequences, with sub-parallel lower and upper boundaries, a narrow zone of folding and thinning and fold axial traces that align in a zone parallel to the salt–sediment interface. Multiple wedge halokinetic sequences form tapered composite halokinetic sequences with convergent lower and upper boundaries, a broad zone of folding and thinning and monoclinal axial traces that are inclined to the diapir. Composite halokinetic sequences have thicknesses and timescales matching those of third-order depositional sequences. They can also stack, with tabular composite sequences having little influence on underlying sequences but development of tapered composite sequences further folding underlying sequences and creating major salt-edge cusps where the composite halokinetic sequence boundaries intersect the salt.

The primary control on composite halokinetic-sequence type is the interplay between sediment-accumulation rate and diapir-rise rate. Tapered composite halokinetic sequences form when sediment-accumulation rate is rapid relative to diapir-rise rate, so that a relatively thick roof develops and is progressively folded during continued diapir rise. Tabular composite halokinetic sequences form when sediment-accumulation rate is relatively slow, so that a thin roof folds over a narrow distance and repeatedly fails. A pattern typical of many diapirs is for deeper tapered composite sequences to transition upwards to tabular sequences because the net differential load on underlying salt increases as minibasins thicken, thereby accelerating salt-flow rate. However, significant third-order variations in sediment supply will alter this pattern, and shortening or extension of a diapir will affect diapir-rise rate and thus halokinetic-sequence development.

Similar halokinetic styles are seen in depositional environments ranging from deepwater to fluvial, but there are key differences. In deepwater settings, composite halokinetic sequence boundaries typically develop due to slow deposition during the transgressive and highstand systems tracts. In contrast, the slowest deposition on the shelf is during the lowstand to transgressive systems tracts, so that composite halokinetic sequence boundaries usually fall somewhere within the transgressive to earliest highstand systems tracts. In subaerial depositional settings, erosional unroofing of the diapir may lead to gradual thinning of the roof (even during relatively rapid sedimentation) so that the zone of folding in a tapered composite halokinetic sequence narrows upward.

The models presented here impact many aspects of the petroleum system in three-way truncations against salt diapirs or steep welds. Variable halokinetic deformation leads to different trap geometries, controls the distribution and facies variations within reservoirs, influences how salt- or weld-seal is evaluated and may explain why some reservoirs are charged with hydrocarbons while others are wet.

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