Salt tectonics in the Sivas Basin, Turkey: outstanding seismic analogues from outcrops

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Abstract
The Sivas Basin in Central Anatolia is possibly the world’s finest open-air museum of salt tectonics structures. It is an elongated Oligo-Miocene sag basin that developed in an orogenic context above the Neotethys suture zone. A mid-Oligocene quiet period during convergence of the Arabian and Eurasian plates allowed the deposition of a thick sequence of evaporites. Erosion of the Taurus Mountains shed clastic sediments northwards over the evaporitic basin. Sediments and deformation propagated from the south, forming mini-basins and associated evaporite diapirs and walls. Following this quiet period, compression resumed in the early Miocene, enhancing the formation of gypsum overhangs and allochtonous sheets. The Sivas outcrops expose classic salt tectonics geometries associated with the development of diapirs: halokinetic sedimentary sequences along diapir walls, welds and evaporite sheets or canopies, minibasins, and overturned minibasin wings (overturned edges of minibasins). These exposures are some of the finest field analogues for classical petroleum provinces controlled by salt tectonics such as the Gulf of Mexico and offshore Angola. We illustrate seismic-scale structures and, in the vicinity of the evaporite bodies, interesting analogues for drilled structures where seismic data do not provide an image.

Introduction
Salt tectonics structures are classic targets for hydrocarbon exploration. Recent progress in seismic acquisition and imaging, such as wide-azimuth towed streamers, and new processing algorithms, such as beam migration, reverse-time migration and full-waveform inversion, allow illumination of near-salt and sub-salt structures with high dips. Nevertheless, salt tectonics studies in the academic world are not common because of the need for high-quality seismic data, usually confidential, and the scarcity and poor quality of field exposures. Publications on field examples deal with radial diapirs exposed in compressive settings and associated with halokinetic sequences, such as in Iran, the Alps, the Pyrenees forelands, and La Popa in Mexico (e.g., Giles and Lawton, 2002). Welds (La Popa, Flinders Range in Australia, Paradox Basin in Utah, Axel Heiberg Island in Canada), canopies (Axel Heiberg), and minibasins (Flinders Range, Axel Heiberg) are less common (Jackson and Harrison, 2006; Rowan and Vendeville, 2006). Some fine analogues, with variable outcrop conditions and accessibility, have been studied extensively by consortia: the Paradox Basin and Axel Heiberg by the Bureau of Economic Geology, Austin, Texas, and La Popa and the Flinders Range by the Institute for Tectonic Studies, New Mexico State University. Those examples have been the subject of numerous oil company training courses.

The Sivas Basin in Central Anatolia has been studied by academics over the last 70 years and interpreted in the thrust tectonics framework of the surrounding Taurides and Pontides ranges. The abundance of evaporites and their apparent complexity were demonstrated to us in June 2011 by the academic group working in the DARlUS consortium for paleogeography (http://istep.dgs.jussieu.fr/darius/). The study of the basin as a salt tectonics analogue started in mid-2012. Satellite images and outcrops are so outstanding that they can already be proposed as analogues for seismic images at this early state of the work.

Geological setting
The Sivas Basin (Figure 1) developed above the Ankara-Erzincan ophiolitic suture zone, which is covered by highly deformed Palaeocene to Eocene marine sediments. The basin covers three major crustal domains, namely the Pontides, Kirêchir and Taurides blocks, and developed in the context of continuing convergence and collision north of the Taurus Mountains. It may be seen as a sag basin that is partly flexural, related to northward thrusting of the Taurus block over the ophiolitic suture zone. The thick mid-Oligocene evaporites, dominantly comprising gypsum and anhydrite, were deposited during a quiet period and are coeval with the Qom and Asmari formations in the Zagros region. This period,
All over the basin, large volumes of gypsum are preserved in walls, at the base and top of minibasins, or as extruded sheets. At this early stage in the study of the basin, it seems that halokinesis followed three main phases:

1) An initial phase at a time of regional tectonic quiescence, dominated by an irregular sedimentary load.
2) A phase of evaporite extrusion at the surface, with overhang and sheet formation above the main unconformity, most likely associated with evaporite withdrawal and the increased rotation of minibasins.
3) The development of a second group of lacustrine minibasins in the mid-Miocene that later underwent the final compressional phase. These lacustrine basins have been uplifted and crop out above massive gypsum bodies, showing that their early emplacement was not uniform. They formed over evaporite feeders during the deflation phase that followed the major stage of formation of allochthonous evaporite bodies and minibasin rotation. Their present attitude, perched on gypsum diapirs, indicates that a late stage of shortening probably reactivated gypsum ascent.

Most minibasins in the south and north have low-angle dips (<30°). In the centre, a set of four well exposed basins have been strongly tilted, in places to the vertical. The cause for the large amount of tilting, which is larger than expected...
from the simple propagation of a sedimentary system, is still debated. It is probably partly syn-sedimentary, caused by the progradation of the overall sedimentary system to the north, possibly enhanced by a basement step identified by interpretation of gravity data, and partly post-depositional in relation to the activation of a Miocene basement thrust. These four minibasins contain exposures of the finest known analogues of salt tectonics structures, the two most outstanding being Emirhan and Karayün.

**Analogue experiments using a scanner**

In 2010, in order to better understand the formation of the minibasin wing structures drilled recently in the Gulf of Mexico, analogue sand-silicone models have been run at IFP Energies Nouvelles (Callot et al., 2013). Models were run in an X-ray tomography medical scanner in order to image, in a completely non-destructive manner, the three-dimensional internal structure that formed during the course of the modelling. The modelling was designed to reproduce the development and subsidence of minibasins deposited above a thick evaporite layer. Basins were initiated artificially early in the process by randomly depositing thin pods of sediments. Progressive subsidence of the deposited layers created accommodation space filled by further sequential sedimentation and erosion of relief. This set of experiments, carried out before our study of the Sivas Basin, has reproduced most observed geometries that can be encountered in the basin. Some of these models are compared with field examples and seismic lines in Figures 2 and 3.

**Seismic-scale geometries: direct analogues**

The satellite image of the ‘core area’ (Figure 2b) shows geometries that will be recognizable to anyone who has seen seismic lines or cross-sections of minibasins (e.g., Figure 2a; see also Google Earth images around 39°42’25”N, 37°16’00”E). In this part of the basin, a set of four minibasins have been tilted to expose the bases of the former basins and their lateral boundaries at the surface, as in a cross-section.

Of these minibasins, the two most spectacular are Emirhan and Karayün (Figure 1). Both basins are completely surrounded by gypsum bodies or welds and exhibit a cumulative thickness of 3.5 km (Emirhan) and more than 4.5 km (Karayün) at outcrop. Their widths are approximately 5 km for Emirhan and 7 km for Karayün.

The Emirhan minibasin (Figure 2) exhibits growth strata along both its western and eastern boundaries. The lower fluvial reddish sequence is thicker to the west than to the east, suggesting strong evaporite withdrawal in the eastern part

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**Figure 2** (a) 3D wide-azimuth seismic section from deepwater Gulf of Mexico (courtesy of TGS). (b) Geoeye satellite colour composite image of the Emirhan minibasin. (c) Cross-section through an analogue sand-silicone model imaged by a medical scanner (courtesy of IFP).
The seismic line in Figure 2a, from a 3D survey in the deepwater Gulf of Mexico, shows two diachronous minibasins having high dips and complex progressive unconformity patterns along the salt wall. The one to the right shows a ‘rocking chair’ pattern, with first a thickening towards the left, followed by a thickening towards the right that resembles the Emirhan basin fill. The vertical scanner section from an analogue experiment, which reproduces the sagging of sand in a very thick silicone layer, has produced a strikingly similar minibasin imaged along a vertical cross-section in Figure 2c.

The nearby Karayün minibasin is more symmetrical than Emirhan (Figure 3b). Bedding dips evolve from 40° at the base to 80° at the top over an outcrop of 4.5 km length perpendicular to bedding. The lower part of the fluvial sequence shows symmetrical sag, wedging towards the former evaporite pilows on both sides. The upper fluvial sequence wedges gently eastwards, whereas it is cut sharply in the west along the weld that was formerly a diapiric wall. The unconformity at the base of the lower Miocene marine sediments is more pronounced in the west, where large halokinetic sequences are visible, than in the east. Bedding in the marine sections is generally parallel, recording a drowning of the fluvial minibasin at a much larger scale. The eastern wall was transgressed and both the Karayün and Akpınar minibasins sagged together in the early Miocene (Figures 1 and 2).

The marked angular unconformity and the almost vertical tilting of the sedimentary sequence in Emirhan is considered to be a consequence of renewed compression in the Sivas Basin in the early Miocene, creating out-of-sequence thrusts propagating from the Taurus Mountains into the basin. In petroleum basins, seismic data at the basin scale allow the overall structure of such basins to be imaged, but do not clearly show the position and geometry of the lateral walls and nearby halokinetic sequences in the sediment.

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irregular surface of a thicker gypsum bed in the upper part of the cliff has formed by flow of the gypsum sheet over it, and exhibits a geometry similar to that of a mountain-top ice sheet.

The second outcrop (Figure 4b) lies in Mescitli along the Kayseri highway south of the town of Sivas. It shows diapiric cross-cutting relationships, a small interbedded gypsum tongue, and a gypsum sheet that is flat-lying above the sediments. Fluvial channels terminate about 10 m away from the vertical diapir wall, where the rates of sedimentation and halokinesis were in balance. Further north, the same contact has a dip of 45° and sharply truncates the fluvial sediments (Figure 4c).

In Figure 5, small compressive salt sheets in the most recent mid-Miocene lacustrine minibasin west of Emirhan (see Google Earth at 39°42'25"N, 37°16'00"E) are compared to a high-resolution seismic image showing analogue geometries at the tip of a shallow salt sheet in the Gulf of Mexico (Roberts et al., 2011). In this case, the folded lacustrine strata demonstrate both the propagation of an extrusive to thrusted evaporite sheet, and also the progressive downbuilding of the lacustrine beds into the thick sheet.

Sub-seismic geometries where field observations help interpret poorly imaged structures

Minibasin growth is recorded by angular unconformities and bed rotation along the basin boundaries with the salt feeders. These structures are rather well imaged on seismic data at the minibasin scale. However, local unconformities, hook or ‘J’ structures in the vicinity of diapir boundaries and welds, often located beneath salt overhangs or canopies, and also the welds themselves cannot be imaged properly even with the most recent seismic acquisition and processing techniques (e.g., seismic lines in Figures 2 and 3). Detailed interpretation is assisted by biostratigraphy and dipmeter data.

Many examples of both growth sequences and halokinetic sequences with unconformities can be seen at different scales in some of the Sivas minibasins (Figure 1). Again, the best outcrops are located along the lateral edges of the Karayün and Emirhan minibasins in the fluvial sequence. The wedges

Figure 4 (a) The Kizilkavraz gypsum sheet at 34°46'N, 37°11'E. The view is to the east of the ridge above Kizilkavraz village, and the location is marked by the red rectangle on the oblique satellite view which shows the overall flat morphology of the hill covered by gypsum with numerous dolines on its surface. (b) and (c) Evaporite wall and glacier near Mescitli at 39°37'20"N, 37°00'15"E. See Figure 3 for seismic analogues.
The angular unconformities define bounding surfaces that separate genetically related packages of halokinetic growth strata, termed halokinetic sequences. Halokinetic sequences were defined by Giles and Lawton (2002) as ‘relatively conformable successions of growth strata genetically influenced by near-surface or extrusive salt movements,’ and are locally bounded at the top and the base by angular unconformities that become disconformable to conformable with increasing distance from the diapir.

Around the basin, the former evaporite walls at the base, edge and top of the minibasin are a succession of welds and pillows (Figures 2 and 6c). The southern boundary, which is the base of the minibasin, is fringed by a 20-m-thick evaporite sheet developed over reddish to greenish silty–sandy sediment about 100 m above the main evaporite (yellow arrow on Figure 2). Its origin is still being discussed because it may be either a depositional level, and thus included in the main evaporite, or the remnant of an early sheet extruded at the surface. The dip view of the suture at Emirhan village (Figure 6c) shows the overturned base of the Emirhan
minibasin, the normal lower dip of the Ilkindi minibasin to the south, and the suture in between, which is a succession of welds and evaporite pillows. The bulk of the pillow is composed of blocky, crystalline, translucent arrow-head gypsum, labelled (1) on Figure 6a, commonly rimmed by a layer of saccharoid gypsum, labelled (2) on Figure 6a.

The two most spectacular structures in the Sivas Basin are almost fully exposed, and one of them allows a comparison with a drilled analogue where seismic data alone are insufficient for a robust interpretation. They are the eastern wall of the Emirhan minibasin (Figures 2 and 7) and the minibasin folded wing structures forming the eastern part of the Karayün minibasin and the western part of the Akpinar minibasin (Figure 8).

The general structure of the eastern part of the Emirhan minibasin has been described above (Figure 2). The basin is composed of a mid-upper Oligocene fluvial formation below the angular unconformity and a lower Miocene marine formation above. The fluvial series thickens westwards, away from the evaporite wall, and exhibits several internal unconformities. Bedding is conformable to the diapiric wall and has been dragged to form a 90° unconformity close to the evaporite. It wedges westwards to an angle of less than 10° to the unconformity at a distance of 200 m away. The unconformity is overlapped by marine sediments, a sequence beginning with a marine conglomerate deposited in the vicinity of the evaporite wall. To the south, the gypsum wall is discontinuous, with alternating thick pillows and welds. Where the beds are dragged and markedly unconformable, the wall is welded. To the north-east, above the unconformity, a large salt stock subsided in the mid-late Miocene to allow the deposition of a patch of lacustrine sediments, now tilted and folded (compare map in Figure 2 and panorama in Figure 7).

The setting is tentatively compared to a section in the contractional part of the Angola gravity tectonic system. The 3D seismic data have been migrated with reverse time migration (Figure 7b). The well was targeting a turbiditic channel below the salt canopy. Although seismic data quality is poor in the vicinity of the well and below the salt stock, the dip data along the well suggest an interpretation which is comparable to the eastern structure of the Emirhan minibasin. Below a 1000-m-thick salt canopy, the well encountered four dip domains as interpreted from images acquired by the oil-based mud imaging tool. The two lower dip domains define the overturned limb of the mini-basin, and the third is just below the salt in an unconformable sequence. These domains are also consistently constrained by biostratigraphy with Oligocene strata below the unconformity and Miocene strata above, a setting which closely mimics the geometries and ages observed in Emirhan. The pseudo-well trajectory drawn at the eastern side of the Emirhan minibasin (Figure 7a) crosses a similar geometry, and would record a similar evolution of the bedding.

The second most outstanding structure is at the contact between the Karayün and Akpinar minibasins (Figure 8; see Google Earth around 39°43'08"N, 37°21'04"E). Once again, the map appears to show a cross-section. The Akpinar minibasin is younger than the Karayün minibasin and mostly filled of marine sediments, apart from its basal succession. The upper part of the marine series transgresses the locally

Figure 7 (a) Growth strata and unconformity in the eastern part of the Emirhan minibasin at 39°42'44"N, 37°15'20"E. Location is shown in Figure 2. The white line marks a pseudo-well trajectory that would show the same dip evolution as the well in Figure 2b. (b) Analogue geometry in deepwater offshore Angola constrained by dipmeter data along the well.
tion satellite images and fieldwork to investigate the geology of the minibasins, focusing on the growth and halokinetic sequences, and their bounding unconformities. This work is likely to enrich the tectonosedimentary concepts developed in other salt basins such as La Popa and the Flinders Range (e.g., Giles et al., 2004).

One of the most difficult issues to address in this world-class analogue will be chronology. Detailed sequence logging has started, but so far it has only been possible to date, rather imprecisely, the lower Miocene marine sediments and the mid-Miocene lacustrine beds. No fossils have yet been found in the lower fluvial formations, so we hope magnetostratigraphy will help to date and correlate these levels. A fine chronostratigraphy would help quantify evaporite movements.

A second important issue is related to the evaporite rheology. In most known land analogues or offshore basins, mobile salts such as halite or sylvite are an important component of the evaporite sequence and are considered responsible for the overall mobility. In the Sivas Basin, only limited evidence of halite has been seen in the form of a few crystals and a salt spring that is exploited through evaporation in salt marshes. No large dissolution or collapsed structures have been observed, but large amounts of gypsum have been preserved everywhere and seem to fully occupy the space created by evaporite movements. The basin seems to have been dominated by gypsum that was mobile enough to produce structures similar to a halite-rich system.

Another important exploration topic is the evolution of facies towards salt walls and the hydrocarbon trapping of vertical fluvial beds in the east of the Karayün minibasin, a geometry similar to the previous example. Both minibasins are welded base to base. The late deflation of the evaporite level below the Akpınar minibasin was probably enhanced by resuming compression in the early Miocene to form a weld. Two small folds, one made of fluvial sandstones and conglomerates of the lower formation in the Karayün minibasin, and the other correlating with the basal marine conglomerate of the Akpınar minibasin, are the final structures of both minibasins on each side of the weld, juxtaposed during shortening and collapse of the beds in the gypsum.

These sedimentary packages are currently interpreted as exotic sections or raft sections coming from remote structures, but when these sedimentary units show reverse polarity, an overturned wing model must be considered. The seismic example from the eastern part of the Gulf of Mexico (Figure 8c) shows a complex termination of a subsalt basin calibrated by more than four exploration wells, showing geometries comparable to the eastern termination of the Karayün minibasin.

**Ongoing research**

The Sivas Basin should become a location for geotourism as it exhibits more evaporite-related structure types and analogues than any other known basin. The area is easily accessible: the field area is less than 50 km from a large city, with good access and excellent outcrop conditions.

Research on this recently discovered field analogue begun in mid-2012, and there is much more to do. Detailed mapping and logging of the series will be conducted with high-resolution satellite images and fieldwork to investigate the geology of the minibasins, focusing on the growth and halokinetic sequences, and their bounding unconformities. This work is likely to enrich the tectonosedimentary concepts developed in other salt basins such as La Popa and the Flinders Range (e.g., Giles et al., 2004).

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issues in the vicinity of salt walls. This topic will be addressed through detailed analysis of transects across diapirs and adjacent sediments, and will include the analysis of the fabrics in the ductile material, the evolution of the facies near the evaporite, and a diagenetic study of the sediments to see how they are influenced by the salts.

The ultimate task will be to model the structural and sedimentary evolution and to transpose the mechanisms revealed by a continental basin to the deep offshore turbiditic setting, which is that of most explored salt basins.

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