

The origin of salt-encased sediment packages: Observations from the SE Precaspian Basin (Kazakhstan)



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ABSTRACT

Intrasalt sediment packages containing siliciclastic sediments, carbonate sediments, or non-halite evaporites such as gypsum or anhydrite are common within most salt sequences. Intrasalt sediment packages may have been deposited before, during, or after salt deposition and be incorporated into the salt by various processes. Understanding the origin and evolution of intrasalt sediment packages may yield important insights into the tectonic and geodynamic history of the basin, and also into the understanding of salt tectonics. Despite the importance of intrasalt sediment packages, currently there is no systematic description of their possible origins and their distinguishing criteria.

This work is divided into three parts. The first part outlines the possible origins of intrasalt sediment packages, as well as criteria to determine if they originated as subsalt, suprasalt or intrasalt sequences. The second part examines how sediment packages that originated on top of salt, such as minibasins, can be encased within salt. Four key encasement processes are proposed: a) salt expulsion from beneath a minibasin experiencing density-driven subsidence; b) salt expulsion from beneath adjacent subsiding minibasins; c) salt expulsion associated with lateral shortening; d) override of minibasins by a salt sheet sourced from elsewhere. The third part of the paper presents a case study from the SE Precaspian Basin, Kazakhstan, where, using a borehole-constrained 3D seismic reflection dataset, the proposed criteria are applied to an area with abundant, newly discovered sediment packages within salt.

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1. Introduction

All natural salt sequences are lithologically impure, containing varying amounts of non-halite material, such as gypsum, anhydrite, sylvite, and other evaporite minerals, along with siliciclastic or carbonate sediments (e.g., Bornemann et al., 2008; Van Gent et al., 2011; Strozyk et al., 2012; Jackson et al., 2014a, 2015). Non-halite material may also be introduced into the salt after deposition; this may include volcanic intrusions (e.g., Gansser, 1992; Lago San José et al., 2000; Stern et al., 2011), material trapped in a suture developed between two salt sheets (e.g., Dooley et al., 2012), material plucked from beneath the salt (Rockenbauch et al., 1998), and entire minibasins or carapace blocks that subside into and are ultimately encased in the salt (Pilcher et al., 2011; Rowan and Inman,

2011; Fiduk et al., 2014). Currently, there are no established criteria for determining the origin of intrasalt inclusions.

Determining the presence and origin of intrasalt inclusions is important not only for understanding the evolution of the salt structure, but also the tectonic history and geodynamic context of salt basins. Recognition of inclusions within salt and their integration in velocity models used in depth migration of seismic reflection data can improve imaging of adjacent and deeper stratigraphic sections, and, ultimately, help define hydrocarbon plays involving intrasalt or subsalt reservoirs.

A sediment package is *encased* (also called *encapsulated*) if it was deposited above salt and was later enveloped by salt flow. How do such intrasalt sediment packages become encased? Understanding the process of encasement may help constrain the age and compaction state of the sediments in the encased package, which can also be important if the packages are to be drilled through for deeper targets or if the packages are themselves targets for hydrocarbon exploration.

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This paper is divided in three parts. The first part addresses the possible origins of intrasalt sediment packages and the criteria that can be used to distinguish them. This section provides aids at the interpretation of whether a given intrasalt sediment package originated below the salt, within the salt, or above the salt. The second part focuses on sediment packages originating above the salt (suprasalt), and presents the criteria that can be used to infer the process of encasement. The third part presents a case study from the Precaspian Basin, Kazakhstan, discussing the origin of a series of abundant, newly discovered, and well-imaged sediment packages within salt diapirs.

2. Origin of intrasalt sediment packages

The terms suprasalt, intrasalt, and subsalt are used here to refer to the current position of sediment packages with relation to salt (Fig. 1a). However, sediment packages that are currently intrasalt could have originated from these three positions: i.e., below the salt, inside the salt, or above the salt (Fig. 1). In this section we describe in detail the three possible origins of sediment packages that are currently contained in salt.

2.1. Subsalt origin

Rocks that are part of the subsalt sedimentary sequence can be incorporated into salt in two ways. First, they may be lifted from the subsalt surface in a process analogous to glacial plucking (Harrison, 1930) (Fig. 1b). This type of plucking has occurred in the Hormuz Salt Basin of Iran, where large blocks of intrusive igneous rocks sourced from the basement have been carried up in diapirs to the surface (Harrison, 1930). Another example of plucking is recorded in Germany, where blocks containing a subsalt reservoir have been encountered in wells within the Zechstein salt sequence. Rockenbach et al. (1998) interpret these blocks as having been plucked from subsalt structural highs and transported up into the overlying diapiric salt.

Second, subsalt sediments may be emplaced into salt by thrust faults detached beneath the salt (Fig. 1b), similar to thrust systems forming in the presence of multiple detachment levels (e.g., Couzens-Schultz et al., 2003; Pichot and Nalpas, 2009). In the absence of subsequent salt flow, these overthrust blocks are still attached to the subsalt section (Fig. 1b). However, if there is significant salt flow after thrust emplacement, the thrust sheets may be detached from their source and end up floating in the salt (Fig. 1b).

Recognition of intrasalt sediment packages sourced from the subsalt section can be very difficult with limited data. If age information is available, the sediments would be older than the depositional age of the salt if the salt is autochthonous. Age is a less reliable criterion in the case of allochthonous salt. In seismic reflection data, the most reliable indicator of a subsalt origin is seeing the source areas from which the blocks were plucked. These might be beheaded thrust faults projecting into salt or excised base-salt high blocks (Rockenbach et al., 1998).

2.2. Intrasalt origin

Another way by which intrasalt sedimentary packages can be formed is to be originally interbedded with the salt (Fig. 1c). Interbedded sediments can form broadly isopachous layers (Van Gent et al., 2011; Strozyk et al., 2012) or, less commonly, minibasins (Clark et al., 1998; Stewart and Clark, 1999). Packages interbedded with salt may be dominated by evaporites (Bornemann et al., 2008; Jackson et al., 2014a, 2015), although almost any lithology is possible (Jackson et al., 2014b).

The most immediately diagnostic characteristic of sediment packages with an intrasalt origin is their age, which should be the same as salt. In addition, a predominantly evaporitic composition may also suggest an intrasalt origin. Finally, sediments originally interbedded with salt should cover a significant area rather than occurring locally like other types of intrasalt sediment packages. The intrasalt origin of such packages may be especially convincing if they extend to areas where the salt has not yet been remobilized and the initial salt stratigraphy is still intact.

2.3. Suprasalt origin

Of particular interest for this paper are sediment packages that are initially deposited above salt and then become encased in salt when overridden by salt sheets (Fig. 1d). Most such packages described to date have been minibasins, although a wide variety of sediment geometries can in principle become encased. An encased minibasin is everywhere overlain by allochthonous salt or equivalent salt weld (Hudec and Jackson, 2011; Pilcher et al., 2011; Rowan and Inman, 2011, Fig. 2). Encased minibasins were first and most thoroughly described in the Gulf of Mexico; thus, almost all documented examples of encased minibasins are associated with thick salt canopies (Pilcher et al., 2011; Rowan and Inman, 2011; Edwards et al., 2014).

One useful feature to help identify an encased sediment package is its age. Any originally suprasalt package being encased into autochthonous salt must be younger than the depositional age of salt. Relation between the sediment package age and salt emplacement age in an allochthonous sheet or canopy might be more complex (e.g., Fiduk et al., 2014). In the simplest case, a sediment package encased in allochthonous salt is entirely younger than the emplacement of the salt sheet. However, many supracanopy sediment packages incorporate carapace (a condensed sequence formed by strata deposited on top of a diapir; e.g., Kilby et al., 2008; Hudec and Jackson, 2011), which typically predates the emplacement of allochthonous salt (Fig. 1d). If the entire sediment package comprises carapace, then the package may be older than the salt sheet emplacement (Fig. 1d).

In the absence of age information, two other observations can suggest that an intrasalt sediment package has formed due to encasement. First, encasement is more likely to produce only isolated sediment bodies, as conditions for encasement are typically localized. In contrast, intrasalt packages are more likely to be of a depositional intrasalt origin if they are widely distributed, reflecting the spatially extensive depositional environments in which they formed. Second, sutures (zones where salt sheets coalesce; e.g., Hudec and Jackson, 2011) may be expected over the top of sediment packages that have been encased, where the salt sheet(s) flowing over the top of the package completed encasement (e.g., Dooley et al., 2012).

3. Encasement mechanisms

Encased minibasins have only been recognized during the past decade thanks to both improvement of seismic data and an increase of available wells aimed at deeper subsalt targets. Thus, it is not surprising that there has been little systematic work on the processes by which this encasement occurs. Studies of encased minibasins in the Gulf of Mexico suggest that a variety of factors may control their encasement, such as salt budget, sedimentation rate, and the relative size of the minibasin among others (e.g., Rowan and Inman, 2011; Edwards et al., 2014). We suggest that there are four principal ways in which minibasins can become encased, each of which has different implications for the source of the encasing salt (Fig. 3). These processes are: 1) density-driven subsidence in

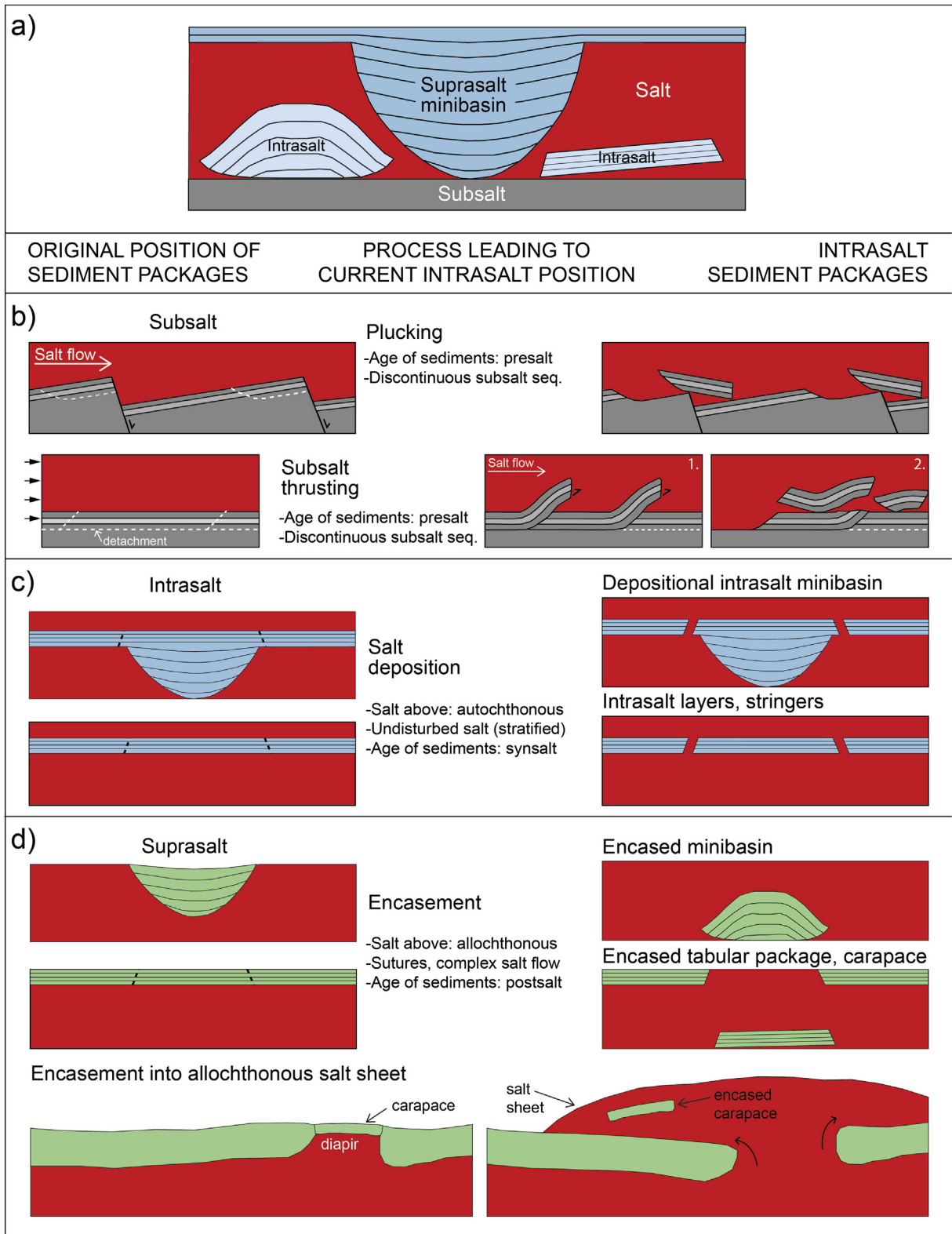


Fig. 1. a) Sketch showing the relative position of sediment packages with respect to salt. b) to d) Possible origins of sediment packages in a current intrasalt position. Intrasalt packages might have been subsalt in origin and been inserted into the salt by plucking or subsalt thrusting (b) of the subsalt sequence (seq.). Intrasalt packages might have been deposited in an intrasalt position originally (c). Intrasalt packages that originated as suprasalt can become encased and appear in intrasalt position (b).

which salt is sourced from below the minibasin, 2) salt expulsion from beneath adjacent minibasins, 3) shortening of adjacent salt structures, and 4) override by a salt sheet sourced elsewhere.

3.1. Encasement due to density-driven subsidence

Density-driven encasement occurs when a sediment package

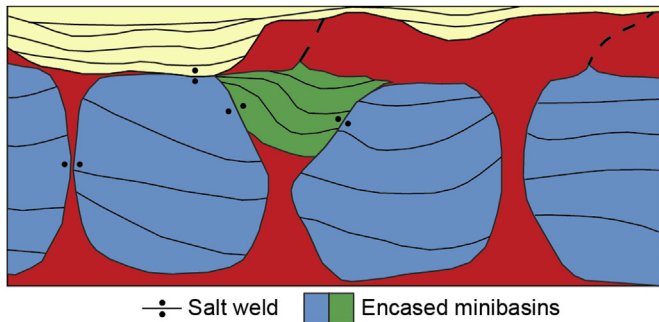


Fig. 2. Schematic representation based on observations from the Gulf of Mexico of variants of encased minibasins (after Pilcher et al., 2011). Encased minibasins may be overlain by allochthonous salt or by equivalent salt welds.

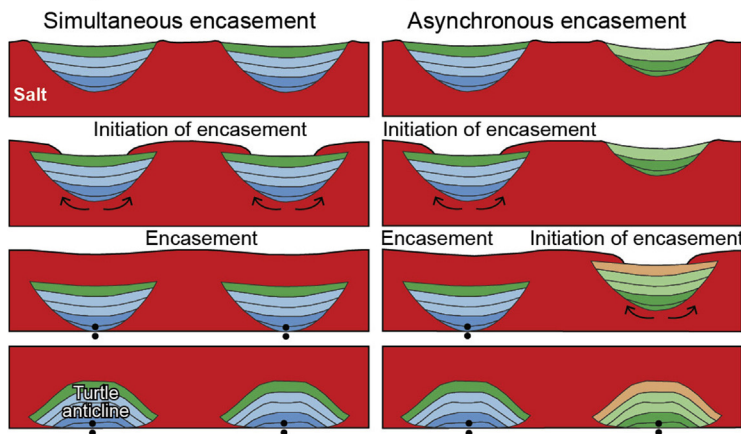
sinks into salt as a result of negative buoyancy (Fig. 3a). This process requires the sediment package to have an average density greater than salt. If a sediment package sinks faster than the sedimentation rate, relief on the edge of salt increases, which leads to flow of salt across the top of the sediment package. Once encasement is complete, the dense package typically continues to sink through the salt

until it welds against the salt base, although this subsidence may be resisted by the rheological behavior of the salt (Wagner and Jackson, 2011; Li et al., 2012), especially in cases where only a small density difference occurs between salt and sediment. In density-driven subsidence, the salt flowing over the top of the sediment package is sourced from beneath the subsiding body.

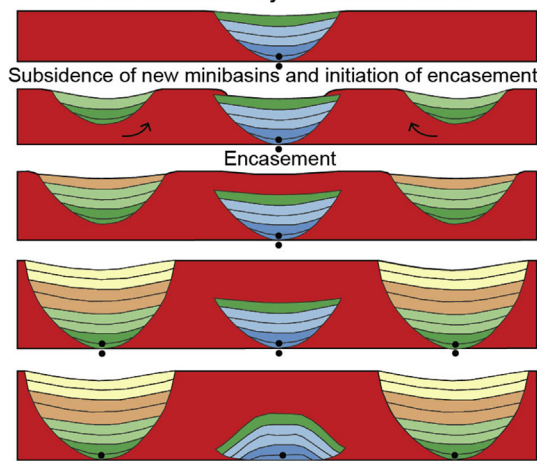
For density-driven encasement to happen, a minibasin filled with siliciclastic sediments must therefore be thick enough to have such a high density (using lithologies and compaction curves appropriate for the basin under study; Hudec et al., 2009). If a minibasin is filled with carbonate-rich sediments or other denser sediments, negative buoyancy might be achieved earlier, with thinner basin fills. An intrasalt sediment package welded against the subsalt strata also suggests that negative buoyancy has been achieved and was, in fact, the process driving encasement.

A difference in the timing of encasement between different sediment packages may provide support for a density-driven encasement model, but this criterion is not diagnostic on its own. If sedimentation rates vary in nearby depocenters, they achieve negative buoyancy at different times and so may become encased diachronously, as recorded by the age of the youngest sediments in each encased package (Fig. 3a). However, encasement may also be triggered by a regional hiatus in sedimentation, allowing nearby

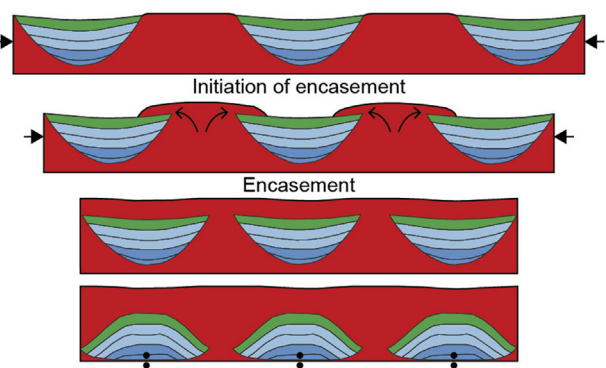
a) Encasement due to density-driven subsidence



b) Encasement by salt expelled from beneath adjacent minibasins



c) Encasement by shortening of adjacent diapirs



d) Encasement by override by another salt body

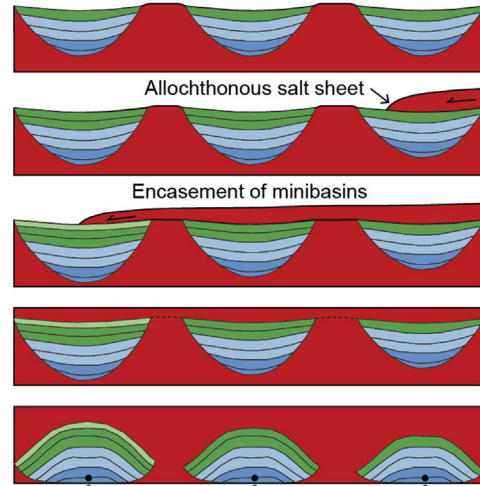


Fig. 3. Sketches showing four encasement mechanisms of originally suprasalt minibasins by a) density-driven subsidence, b) salt expelled from beneath adjacent minibasins, c) shortening of adjacent salt diapirs, and d) override by another salt body.

sediment packages to sink and become encased simultaneously (Fig. 3a).

3.2. Encasement by salt expelled from beneath adjacent minibasins

Salt that is evacuated from beneath adjacent subsiding minibasins can be expelled on top of, and thus encase, an adjacent minibasin (Fig. 3b). This may happen only under specific circumstances. First, the minibasins driving salt expulsion must have significantly higher sediment accumulation rates than the minibasin being encased, or else the sediment surface would rise just as fast as the expelled salt and the package would never become encased. Highly localized sedimentation is therefore required for this mechanism to result in encasement. Second, the package being encased must either be negatively buoyant or fixed in place by some mechanism (e.g., welded at the base or laterally pinned), or else the package would simply float up with the rising salt and be transported away from the adjacent subsiding minibasin. As in the case of density-driven encasement, adjacent minibasins might show similar or diachronous encasement ages, which prevents encasement age from being used as a diagnostic criterion.

3.3. Encasement by shortening of adjacent diapirs

Shortening can squeeze preexisting diapirs and cause them to expel salt rapidly (e.g., Harrison and Jackson, 2014; Hudec et al., 2009; Rowan and Vendeville, 2006), which can ultimately lead to encasement of sediment packages (Fig. 3c) (e.g., Kergaravat et al., 2016; Gradmann and Beaumont, 2016; Rowan, 2002). In this case, nearby sediment packages can become encased even if they are positively buoyant (Hudec et al., 2009).

Several factors can suggest that encasement has occurred by shortening. First, there may be regional, independent evidence for a syn-encasement shortening event, such as time-equivalent thrusting. Second, the encased packages may contain internal evidence consistent with shortening (e.g., folds and thrusts; Hudec et al., 2005; Hudec et al., 2009). Third, all encased packages in an area should be encased at the same time (the time of shortening), so the age of the youngest sediments in nearby encased packages should be roughly the same. Shortening offers a way to encase sediment packages that are positively buoyant (Hudec et al., 2009). Sedimentary packages that are fixed in place (e.g., welded or laterally pinned) would be more easily encased, as they would be prevented from floating away. Shortening may be indicated if large numbers of thin (and so presumably less dense) sediment packages are encased.

3.4. Encasement by override by another salt body

The preceding encasement mechanisms all apply to a sediment package resting above a continuous salt layer from which the encasing salt is sourced. The final mechanism, by contrast, envisions suprasalt sediment packages being overridden by a far-travelled allochthonous salt body (Fig. 3d) (Hudec and Jackson, 2006; Dooley et al., 2012). The most common processes by which this override can occur are allosuturing (i.e., override by a separate salt sheet) and salt overthrusting (Dooley et al., 2012).

Sutures related to overthrusting can be inferred from their presence in the midst of a fold-and-thrust belt or other contractional tectonic regime. Allosutures and autosutures are typically recognized by mapping trails of inclusions lying along the suture, or through identification of multiple feeders in the case of allosutures (e.g., Dooley et al., 2012).

4. Intracaspian sediment packages in the southeastern Precaspian Basin

4.1. Tectonostratigraphic framework

The Precaspian Basin is located at the northern edge of the Caspian Sea in Kazakhstan and Russia (Fig. 4). The basin is 600 km by 900 km and, at its center, >20 km of sedimentary rock overlies crystalline basement. Tectonically, it is located at the southeastern edge of the East European Craton and to the south of the Russian Platform. The Precaspian Basin is limited to the east by the N-S trending Ural orogenic belt and to the southeast and southwest by the Scythian and Turanian platforms, respectively (Fig. 4; Brunet et al., 1999; Natal'in and Şengör, 2005).

The Precaspian Basin was initiated in the Devonian, when the Precaspian rift system developed (Nikishin et al., 1996). The Uralian orogeny began in the early to late Carboniferous due to the collision of the Kazakh and European plates. The eastern part of the Precaspian Basin became part of the foredeep of the Urals, which had begun to grow along the eastern margin of the basin (Puchkov, 1997; Gralla and Marsky, 2000). During the Early Permian, the Precaspian Basin was isolated from the Paleo-Tethys by uplift in the south related to accretion of the Turan and Scythian blocks (Brunet et al., 1999). At this time, Kungurian (Early Permian) evaporites (mainly marine halite) and shales were deposited across the basin, reaching a thickness of up to 2500 m near the basin center (Fig. 5; Volozh et al., 2003). The evaporitic sequences in the center pass into siliciclastic sediments near the southeastern margin, and to carbonates to the northwest (Volozh et al., 2003). The current limits of the Precaspian Basin correspond roughly to the extent of the Kungurian salt (Fig. 4b). Deposition of evaporitic successions continued during the Kazanian (Late Permian) in the central and northern parts of the Precaspian Basin, until the total Kungurian–Kazanian evaporite succession reached a total thickness of up to 4500 m in the center of the basin (Volozh et al., 2003).

During the Late Permian, erosion of the areas to the east and south of the basin resulted in an influx of sediments and deposition of a predominantly shallow-marine succession. Thus, while Kazanian evaporites were being deposited in some parts of the basin, the equivalent sequence in the eastern and western parts of the basin is represented by siliciclastic sediments (Volozh et al., 2003).

Given the large size of the basin, there are relatively few published works in English that focus on the post-salt sequence of the Precaspian Basin (e.g., Sokolova et al., 1973; Kukhtinov and Crasquin-Soleau, 1999; Gralla and Marsky, 2000; González-Muñoz et al., 2001; Barde et al., 2002a, 2002b; Volozh et al., 2003; González-Muñoz and Carballo-García, 2004). Within the Upper Permian sequence, the Ufimian, Kazanian, and Tatarian stages can be distinguished, and, owing to their relevance for this study, we describe the deposits of these three stages with emphasis on the eastern Precaspian Basin (Fig. 5) (Sokolova et al., 1973).

The Ufimian is divided into two units. The lower unit comprises a 200- to 300-m-thick sequence of sandstones, claystones, and siltstones. The upper unit is of comparable thickness and is mainly composed of sandstones. Both units are interbedded with halite, anhydrite, and sporadic limestones (Sokolova et al., 1973; Kukhtinov and Crasquin-Soleau, 1999).

The Lower Kazanian succession records a marine transgression, and the deposition of the Kalinovskaya suite, a <200-m-thick succession of claystone, dolomite, and limestone (Kukhtinov and Crasquin-Soleau, 1999; Huvaz et al., 2007). In the eastern Precaspian Basin, the equivalent sequence is c. 700 m thick and is dominantly composed of sandstones, siltstones, mudstones, and limestones interbedded with salt (Kukhtinov and Crasquin-Soleau, 1999). The Upper Kazanian sequence is dominated by sandstones

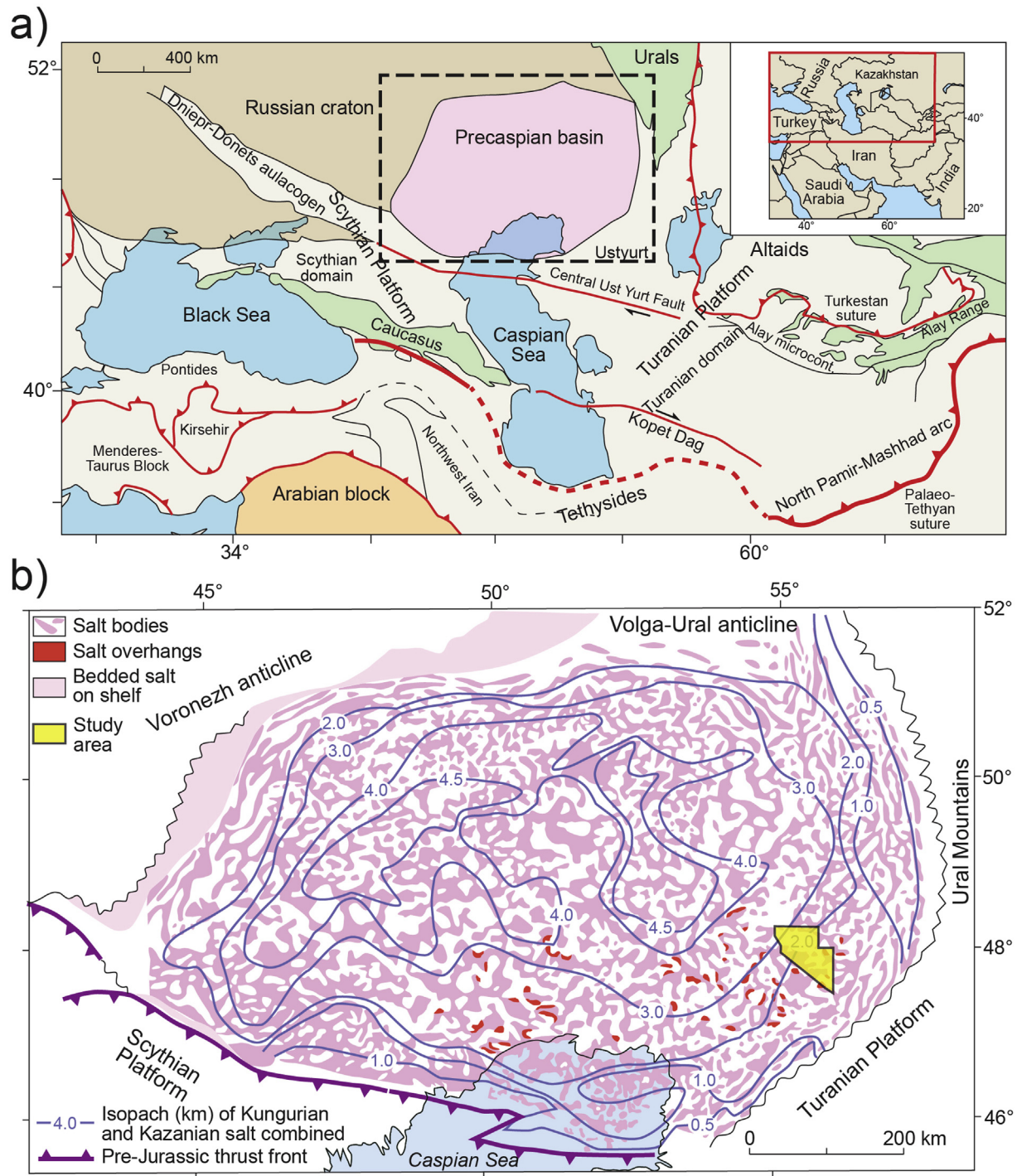


Fig. 4. a) Tectonic elements in the broader Caspian region (after Natal'in and Şengör, 2005). Major orogenic belts are green, and the Precaspian salt basin is pink. Dashed black area is shown in (b). b) Map of the salt bodies (in pink) within the Precaspian Basin (modified from Volozh et al., 2003). Location of the study area, the Zharkamys West 1 block (ZW-1), is yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interbedded with mudstones, with an estimated thickness of 400–500 m (Kukhtinov and Crasquin-Soleau, 1999). Thus, the Kazanian section in the eastern Precaspian is composed of sandstones interbedded with anhydrite, silty shales, and halite that have been interpreted as a sedimentary succession deposited in an evaporitic ephemeral lake (Barde et al., 2002a).

In the Tatarian, intermittent deposition of evaporites ceased, and only continental siliciclastic sediments were deposited (Barde et al., 2002b). During the early Tatarian, a 600- to 800-m-thick

sequence of mainly red clays was deposited, which is overlain by an up to 600-m-thick sequence of interbedded claystones, siltstones, and sandstones (Sokolova et al., 1973; Kukhtinov and Crasquin-Soleau, 1999). An unconformity, which is not always identifiable, separates the Upper Permian and Triassic sequences (Sokolova et al., 1973; Barde et al., 2002a).

During the Triassic, sedimentation was dominated by continental facies (Sokolova et al., 1973), with fluvial-deltaic systems and alluvial fans mainly sourced at the Urals and South Emba region

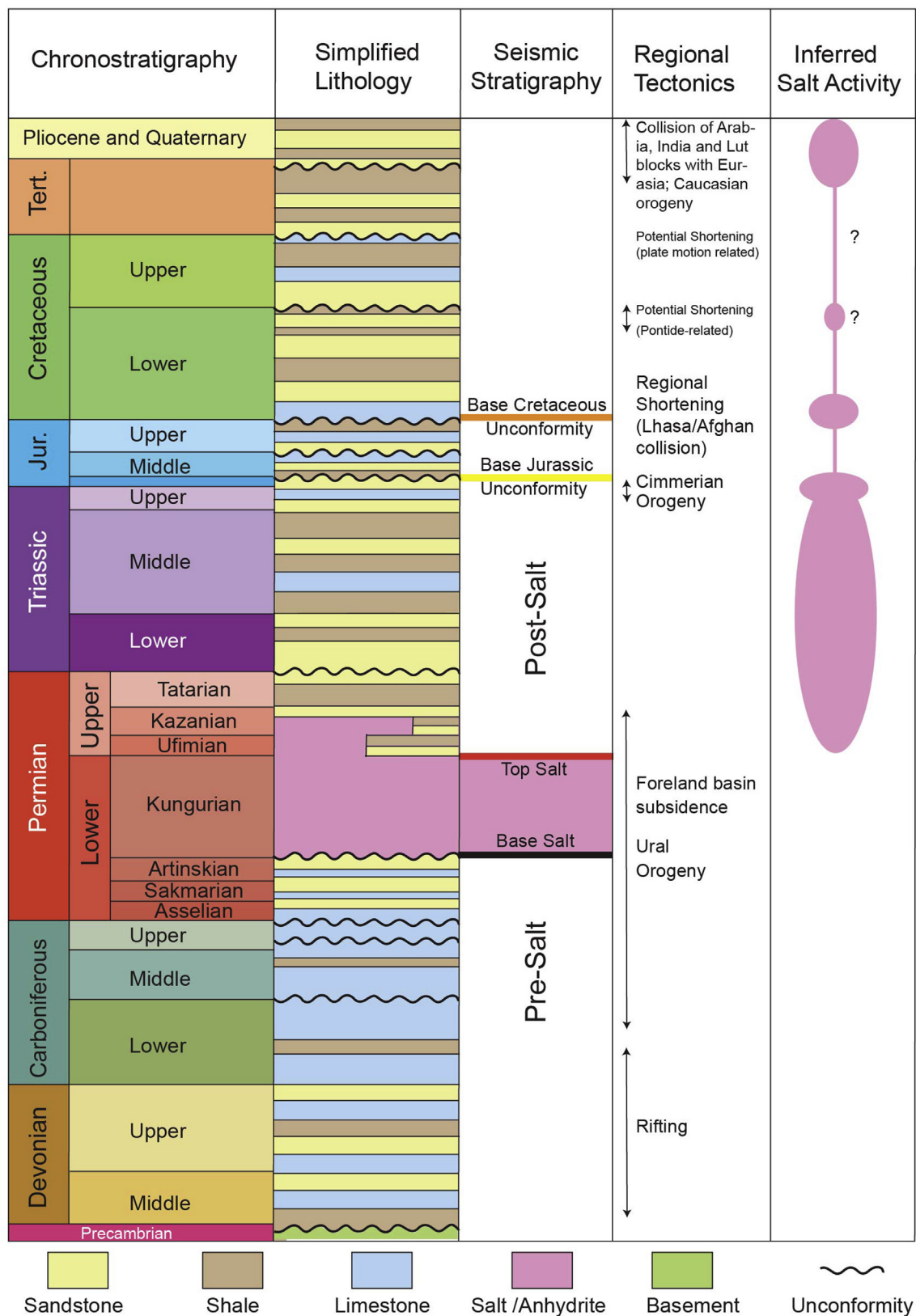


Fig. 5. Stratigraphic framework with the key units of the eastern Precaspian Basin (modified from Barde et al., 2002b). The key seismic stratigraphic markers are color coded. Main tectonic events and inferred salt-tectonic stages are also indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(González-Muñoz et al., 2001; Barde et al., 2002b). The Cimmerian orogeny eventually closed the Paleo-Tethys Ocean, which, during the Late Triassic to Early Jurassic, lay south of the Precaspian Basin. This important tectonic event is marked by a major unconformity that can be observed over most of the Paratethys region (Şengör, 1984). Erosion and uplift associated with the Cimmerian orogeny are recorded in the Precaspian Basin as a widespread angular unconformity at the base Jurassic (Alexander et al., 1999; Volozh et al., 2003). Later collisional events related to the convergence of Arabia

and India with Asia are also recorded in the Precaspian Basin by the development of a suite of unconformities (i.e., base Cretaceous, base Aptian, Miocene, and Pliocene) and by evidence for diapir squeezing and roof arching (Fig. 5) (Alexander et al., 1999; Volozh et al., 2003).

4.2. Study area

The study area is located in the Zharkamys West 1 exploration

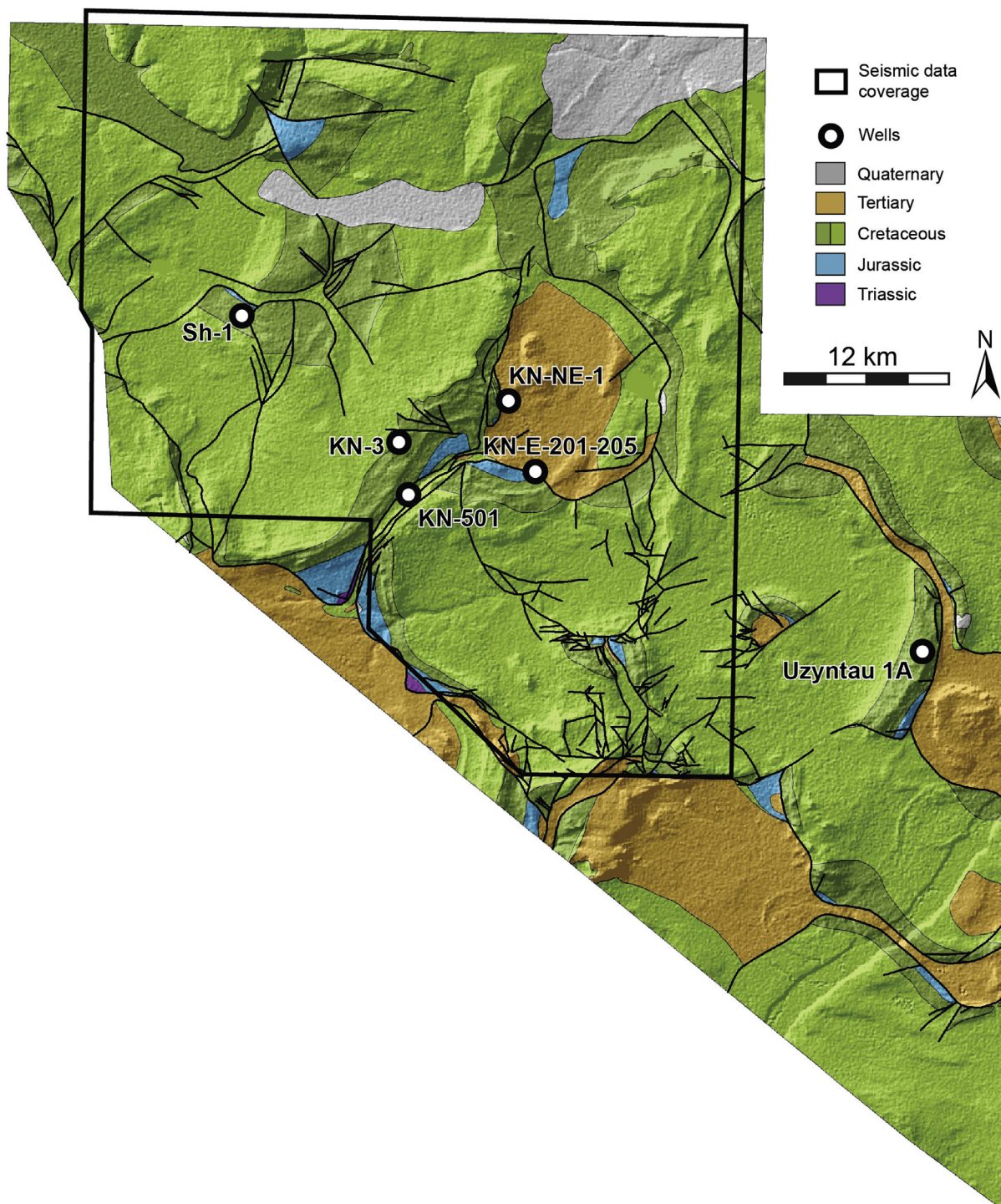


Fig. 6. Simplified surface geology map of the Zharkamys West 1 block showing the coverage of the PSDM seismic data (black outline), fault traces (thin black lines), and location of the wells mentioned in this study.

license block (ZW-1). The ZW-1 block is located onshore in the southeastern margin of the Precaspian Basin (Fig. 4). More than 60 percent (2535 km²) of the block is covered by a 160-fold 3D pre-stack depth migrated seismic reflection survey (see coverage extent in Fig. 6) acquired in 2011. Most of the older boreholes drilled within the ZW-1 block only penetrate the shallowest sections (Jurassic–Cretaceous), and only a few boreholes penetrate deeper sections. For example, well Uzyntau 1A (location in Fig. 6) was drilled to a total depth of 3536 m, reaching Kazanian sandstones at the base of a suprasalt minibasin. Borehole data have been used where available to constrain lithology, age, and present depth-density profiles of the penetrated rocks.

Four key seismic surfaces were mapped across the study area: the base and top of salt, base Jurassic, and base Cretaceous (Fig. 5). The top-salt horizon defines a coarse polygonal framework of salt walls and diapirs. The tallest diapirs are flat-topped (up to 5700 m high) culminations at the junctions between narrow (0–6.5 km), lower-relief salt walls (up to 5300 m) (Fig. 7a). The salt walls and diapirs bound subcircular to ovate suprasalt minibasins, under which salt is very thin or absent due to welding (purple colors, Fig. 7a). These suprasalt minibasins are up to 10 km in diameter and more than 4 km thick (Fig. 7a and b).

Averaging the present salt isopach over the entire study area suggests an initial salt thickness of 2500–3000 m, consistent with regional estimates of salt thickness in this part of the Precaspian Basin (Volozh et al., 2003). Furthermore, the upward transition from a bowl-shaped minibasin geometry to one that is wedge shaped, a transition that is inferred to mark the timing of minibasin grounding (*sensu* Rowan and Weimer, 1998), occurs at a minibasin thickness of 2500–3000 m within many of the suprasalt minibasins. However, this estimate of primary salt thickness contains two major sources of uncertainty. First, an unknown volume of salt has been lost to dissolution. If there has been significant dissolution, then initial salt thickness would have been greater than 2500–3000 m. Second, we argue elsewhere that significant shortening occurred between minibasins, thus thickening the salt (Duffy et al., 2017). If so, the original thickness may have been less. Given these uncertainties, the suggested salt thickness should only be considered a rough estimate.

4.3. Intrasalt sediment packages

The seismic survey covering the ZW-1 block was designed to image the presalt sequence; it therefore also provides a good image of the intrasalt structure. We observe many intrasalt reflections, and, while incoherent amplitudes or individual reflections characterize some of the intrasalt reflectivity, we have identified and mapped more than 40 coherent, continuous reflection packages (Fig. 8). These intrasalt packages have limited spatial extent (<12 km in length), are up to 3000 m thick, and are mainly located at the lower 2–3 km of the salt sequence (Fig. 7b). In most cases, these packages are welded to subsalt strata. The spatial distribution of the intrasalt packages is shown on an interpreted depth slice at 4800 m (Fig. 8), a depth at which all the intrasalt packages are intersected. As shown in the depth slice, intrasalt packages occur in the diapirs and typically tend to be in weld contact with suprasalt minibasins. Bedding within intrasalt packages that are welded against suprasalt minibasins typically strikes subparallel to the weld and dips toward the suprasalt minibasins (Fig. 8). Furthermore, the intrasalt packages are gently folded, especially in intrasalt packages located near the centers of the diapirs.

Intrasalt packages are 800–2500 m thick, although most are 1400–1700 m thick (Fig. 9). The thinnest intrasalt reflection packages (<1000 m) surround the suprasalt minibasins, whereas the thickest packages are typically located in the center of the salt

diapirs formed at the salt wall junctions (Fig. 9). The upper and lower bounds of some of the intrasalt packages are difficult to map despite the presence of clear intrapackage reflectors. Thus, the thicknesses of these less-well-imaged packages have not been measured. They are mapped as “undifferentiated intrasalt packages” in Fig. 9 and indicated with dashed lines in the seismic sections (Fig. 10). Within the mapped packages, we recognize two types of intrasalt geometries in the ZW-1 dataset: minibasins and tabular packages.

4.3.1. Minibasins

Some intrasalt packages, which are 1400–1600 m and locally up to 2500 m thick, are bowl shaped, with internal reflections that show clear terminations against salt and display converging and onlapping geometries (Fig. 10). Based on their geometry, we interpret these packages as minibasins. Many have preserved their inferred primary synclinal geometry (Fig. 7), whereas others have been inverted to form turtle anticlines (Fig. 10) or half-turtle structures.

The two thickest intrasalt minibasins have been drilled by the KN-501 and KN-E-201-205 wells (Fig. 11a). The KN-E-201-205 well, drilled to 1870 m, discovered hydrocarbons, leading to drilling of two more wells on that structure. The wells drilled the up-dip corner of an intrasalt minibasin and encountered an upturned flap of steeply dipping to overturned strata comprised of 300–700 m of Kazanian (based on palynological data) fluvial sandstones, silty claystones, silty marls, and a 60-m-thick halite layer (Fig. 11b) that pinched out laterally into clastic rocks.

The KN-501 well targeted a much more deeply buried intrasalt package and was drilled to 3990 m. The intrasalt package intersected by the well was nearly flat-lying and comprised 300 m of Upper Permian (probably Kazanian) section composed of red shale, halite, and anhydrite interbedded with thin siltstones. Below this section, the well encountered 160 m of gray shales, marls, and thin limestones and anhydrite, which, based on palynological data, are dated as Ufimian.

Because both drilled intrasalt minibasins are younger than the overlying Kungurian salt, we conclude that they are encased. The other undrilled intrasalt minibasins have seismic facies and reflection patterns similar to the drilled minibasins, although they are thinner (Figs. 10 and 11). In the absence of other information, we suggest that the undrilled intrasalt minibasins are also younger than salt, and thus encased. Models for the encasement process are discussed in the next section.

The youngest section in each drilled encased minibasin was Kazanian, but correlation between the two wells suggests that the Kazanian section penetrated in the KN-E minibasin was younger than the Kazanian penetrated in the KN minibasin (Fig. 11). Thus, the KN-E minibasin was encased later than the KN minibasin.

One question posed by the existence of the encased minibasins is the relative age of the encased and the suprasalt minibasins. Do the encased minibasins represent an early phase of minibasin development now lying entirely inside salt and overlain by a younger generation of suprasalt minibasins? Or are the encased minibasins the same age as the deeper parts of the suprasalt minibasins? There is no age control on the deeper parts of the suprasalt minibasins imaged in the seismic data of the study area, thus these questions cannot be directly answered. However, deeper wells drilled to the southeast of the ZW-1 block have found Ufimian to Kazanian section in the deeper parts of suprasalt minibasins, coeval with the encased minibasins of the study area (e.g., the Uzyntau 1A; Fig. 6a). Because of the uncertain age correlations, we elect to use the terms *encased* and *suprasalt* to refer to the two sets of minibasins and avoid more age-specific terminology such as *primary* and *secondary* (Pilcher et al., 2011).

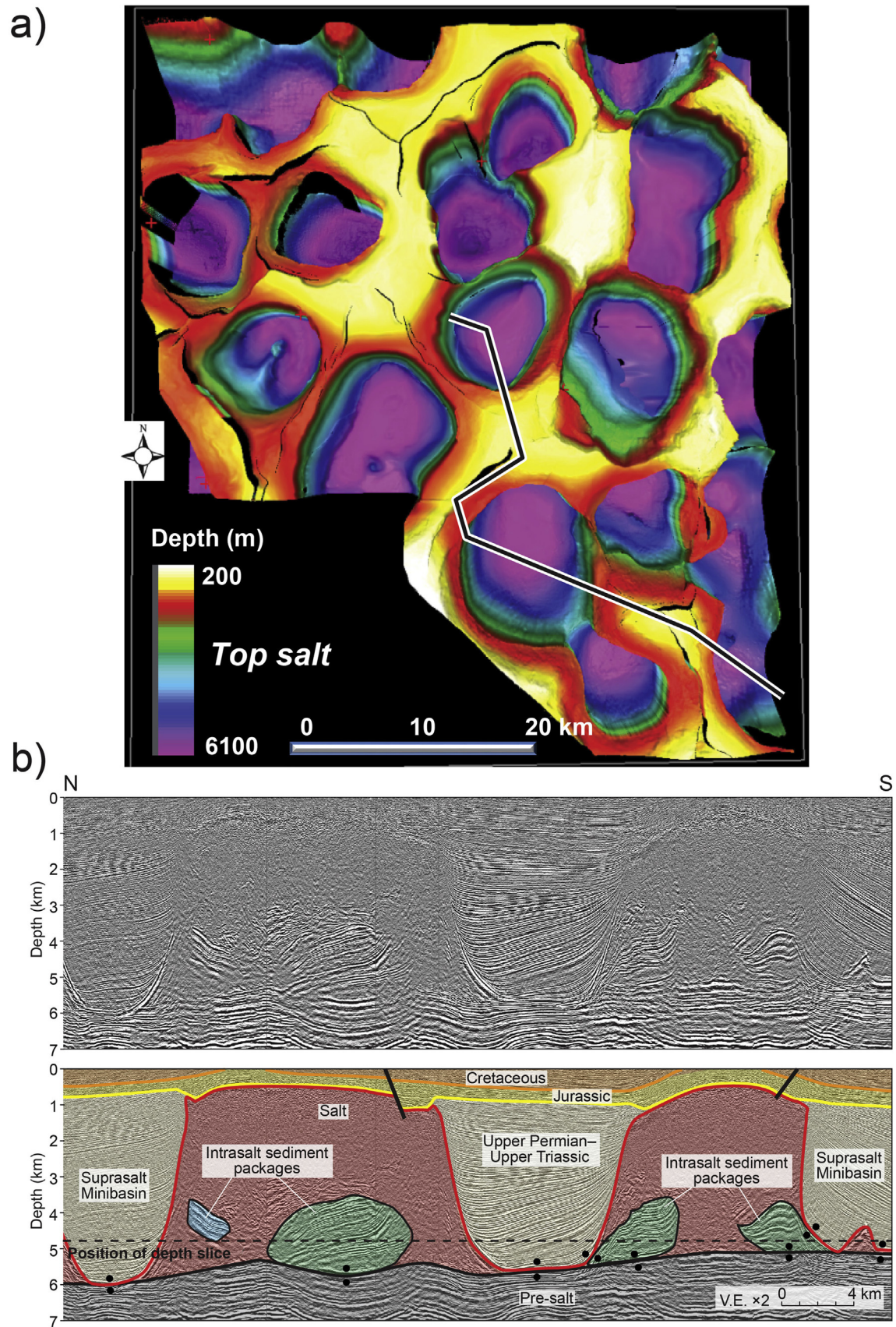


Fig. 7. a) Top-salt structure map of the Zharkamys West 1 block extracted from the PSDM 3D seismic data. b) Uninterpreted and interpreted seismic cross section illustrating sedimentary bodies (e.g., encased minibasins) within the salt diapirs. Location of cross section is indicated in (a).

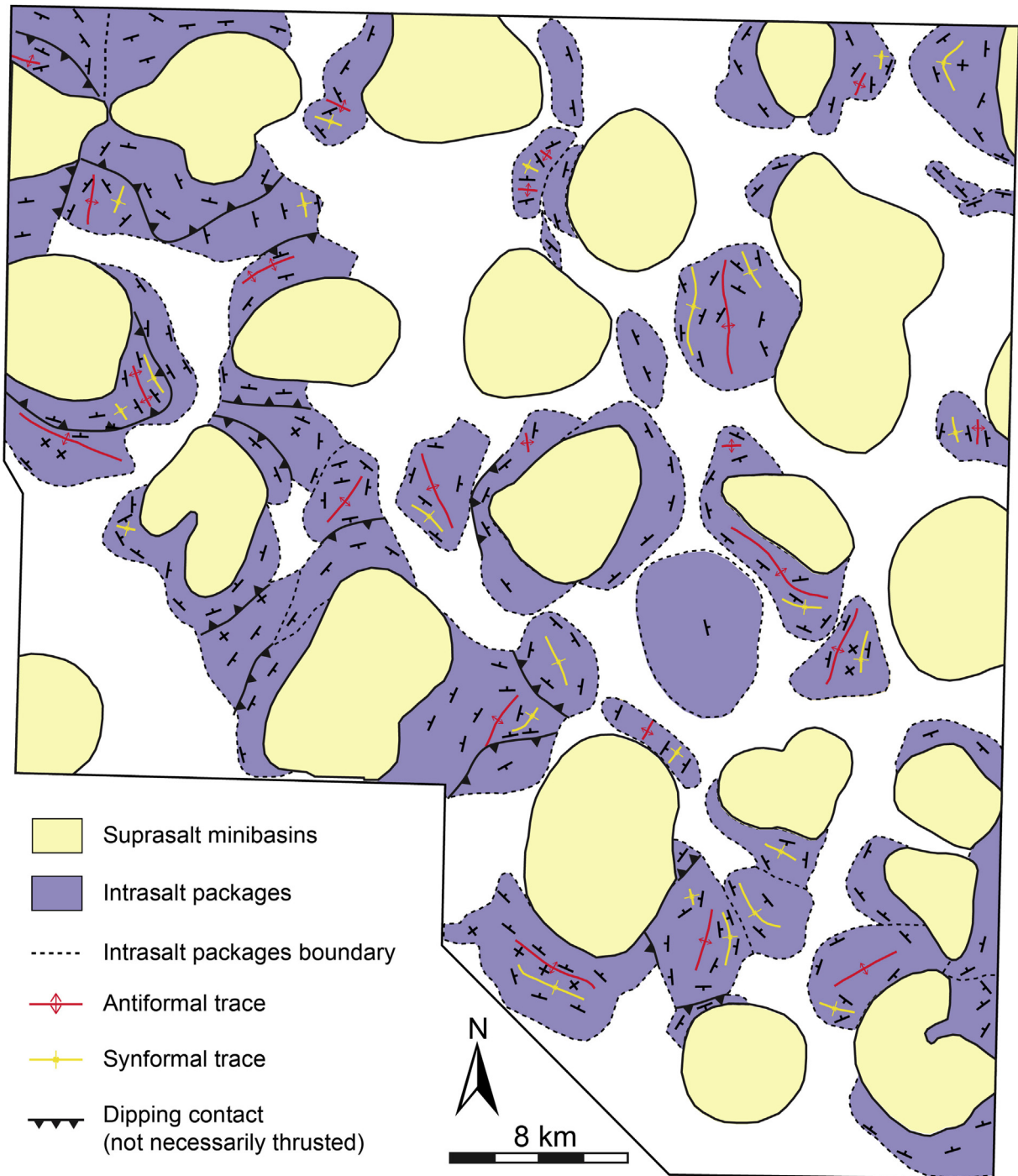


Fig. 8. Structural map at depth slice 4800 m. Suprasalt minibasins are yellow. Interpreted intrasalt sedimentary packages are purple. Where one intrasalt package overlies another, the triangles of the contact line point toward the overlying package. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3.2. Tabular packages

Some intrasalt sediment packages have no clearly defined synclinal depocenter, but instead form elongated tabular packages (Figs. 10b and 12a and b). These packages are typically 700–1000 m thick and up to 12 km long, and are thus significantly thinner and have higher aspect ratios than the encased minibasins. The tabular packages are dominated by high-amplitude, continuous reflections, and they lack the internal truncation and onlap relationships seen in the minibasins. Some tabular packages are gently folded.

Like the encased minibasins, tabular packages tend to lie within

the lower portion of salt, but they are not always welded to subsalt strata. They are commonly locally welded below the overlying suprasalt minibasins. Tabular packages thin laterally where they are pinned between suprasalt minibasins and the subsalt strata (Figs. 10b and 12b). Thus the “tabular packages” are not everywhere strictly tabular, but may locally vary in thickness. Because the tabular packages thin only beneath the suprasalt minibasins, we interpret the thinning to be secondary and related to post-depositional deformation, rather than having a primary (depositional) origin. Where tabular packages are juxtaposed against

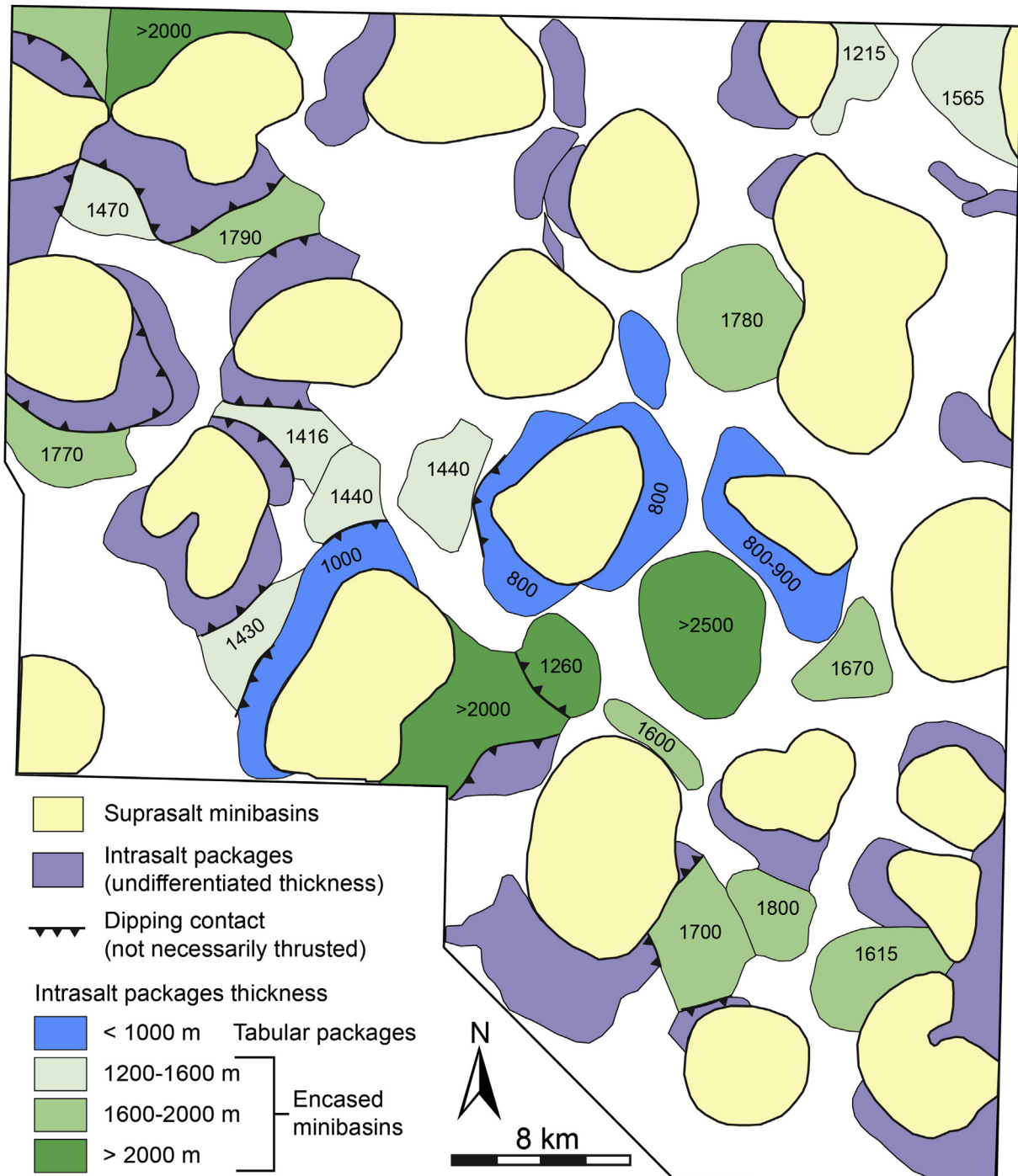


Fig. 9. Thickness map of the two main types of intrasalt sedimentary packages: tabular packages and encased minibasins. Only packages having clear boundaries show thickness measurements.

encased minibasins, the tabular packages tend to overlie the encased minibasins (e.g., Fig. 12). However a complete juxtaposition, with a tabular package lying completely over the top of an encased minibasin, is not observed. Instead, the edge of a tabular package overlaps the edge of an encased minibasin (Fig. 12). The tabular bodies occur only in the central part of the study area, where they are clustered (Fig. 9).

No well has been drilled into the tabular packages. However, three lines of evidence suggest that they may be composed of layered evaporites. First, their densities are evidently comparable to

or slightly greater than halite based on their occurrence at the base of the salt sequence. This is true despite the fact that they are too thin to have reached this density merely by compaction of clastic sediment (see next section). Thus, we suggest they may contain denser rocks, such as evaporites or carbonates. Second, the seismic facies, high-amplitude and low-frequency units with transparent units, may indicate the presence of bedded evaporites (e.g., Cartwright et al., 2012; Fiduk and Rowan, 2012; Jackson et al., 2014a,b; 2015). Third, the thinning of the tabular packages where pinned beneath suprasalt minibasins, together with intrapackage

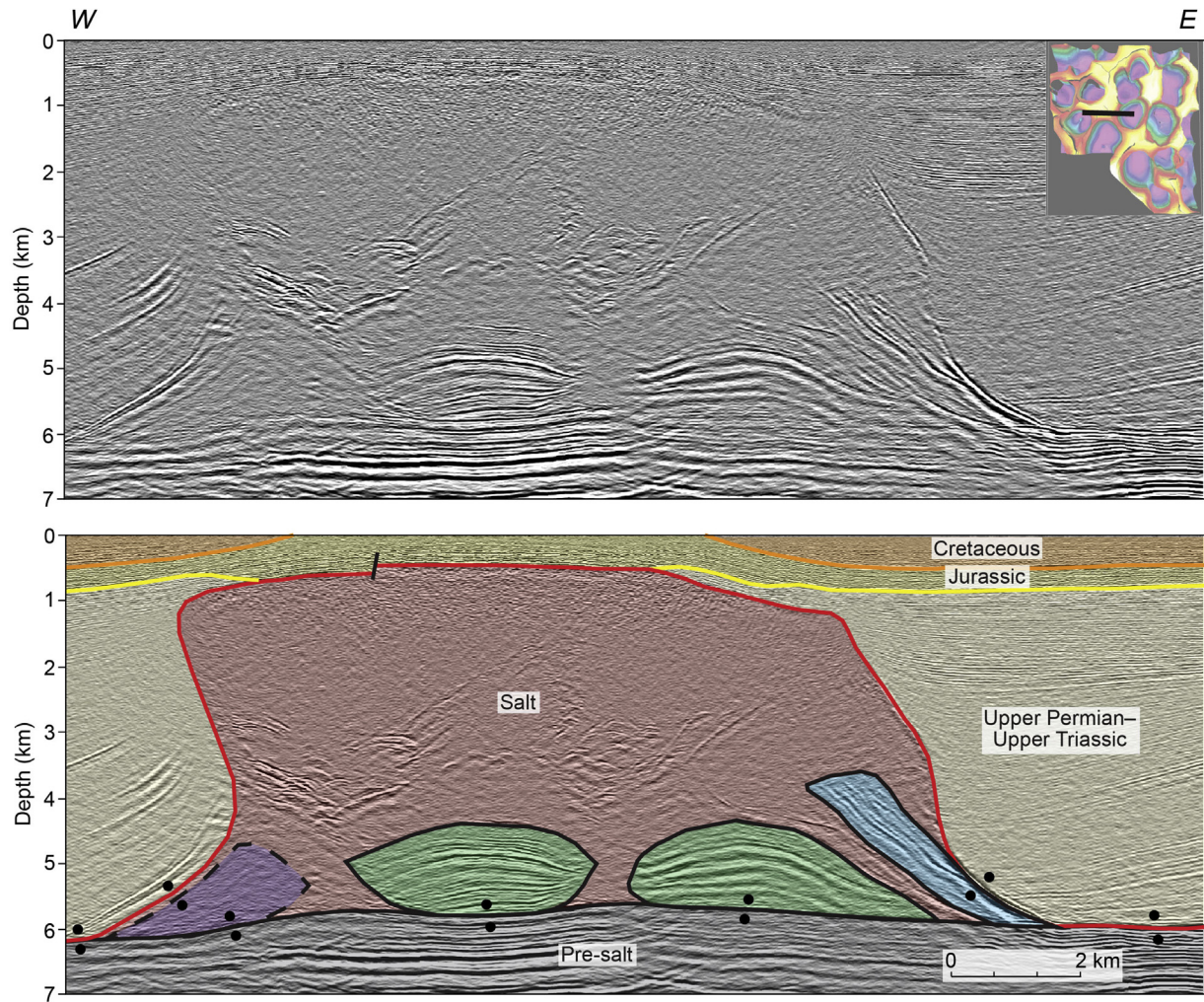


Fig. 10. Uninterpreted and interpreted seismic cross section illustrating examples of intrasalt sediment packages (encased minibasin in green, tabular sediment packages in blue, and undifferentiated intrasalt packages in purple). Location of the cross section is indicated in the inset map on the top right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

disharmonic folding, suggests the presence of a multilayer sequence containing a mobile unit, such as halite, alternating with a stronger unit, such as siliciclastic rocks or carbonate-rich rocks.

5. Discussion: encasement mechanisms in the study area

5.1. Density considerations

One of the most striking features of the encased sediment packages in the ZW-1 block is that they all cluster near the base of salt, suggesting that their average densities are greater than halite. This is true regardless of package thickness. Density-depth curves for siliciclastic sediments tend to be based on marine successions (e.g., Hudec et al., 2009) so may not be appropriate for the fluvial-lacustrine sediments encountered in the Precaspian Basin. Negative buoyancy might be reached at different thicknesses in adjacent minibasins, depending on the type and, thus, density of sediments deposited in those minibasins. For example, the deep-water sediments that fill the minibasins in the Gulf of Mexico would require thicknesses of >2300 m to reach negative buoyancy, according to the different depth-average density curves presented by Hudec et al. (2009, and references therein). However, in some other basins, marine muds have depositional densities greater than salt (Baudet and Ho, 2004) or compact relatively rapidly and attain

densities higher than salt at shallower depths than occur in the Gulf of Mexico (e.g., Ramdhan and Goult, 2010; Yin et al., 2011). Continental fluvial clastic sediments (Barrash and Reboulet, 2004), and especially carbonates (e.g., Royden and Keen, 1980; Schmoker, 1984), might be initially denser than salt or reach negative buoyancy early in their burial history.

Most of the wells in the study area do not have neutron-density logs, but we have compiled data from three wells that do (Fig. 13a; well locations shown in Fig. 6a). The three wells define a depth-density curve that can be used to derive the average density with depth (black line, Fig. 13b, c, and d). The log density of the Kun-gurian salt in KN-NE-1 and KN-E-201 is only 2025–2040 kg/m³, which, due to the tendency of neutron-density logs to under-represent salt densities (e.g., Alger and Raymer, 1963), corresponds to corrected, “normal”, halite densities of around 2200 kg/m³. According to these data, sediments in SE Precaspian would require a thickness of approximately 2500 m to reach negative buoyancy (Fig. 13). Few of the encased minibasins reach this thickness, but all are clustered near the base of salt, so there must be some way of increasing the average density of the intrasalt sediment packages. A potential explanation is that siliciclastic sediments in the encased minibasins and the tabular packages are interbedded with dense evaporites, such as anhydrite. This interpretation is supported by the fact that both wells drilled into encased minibasins

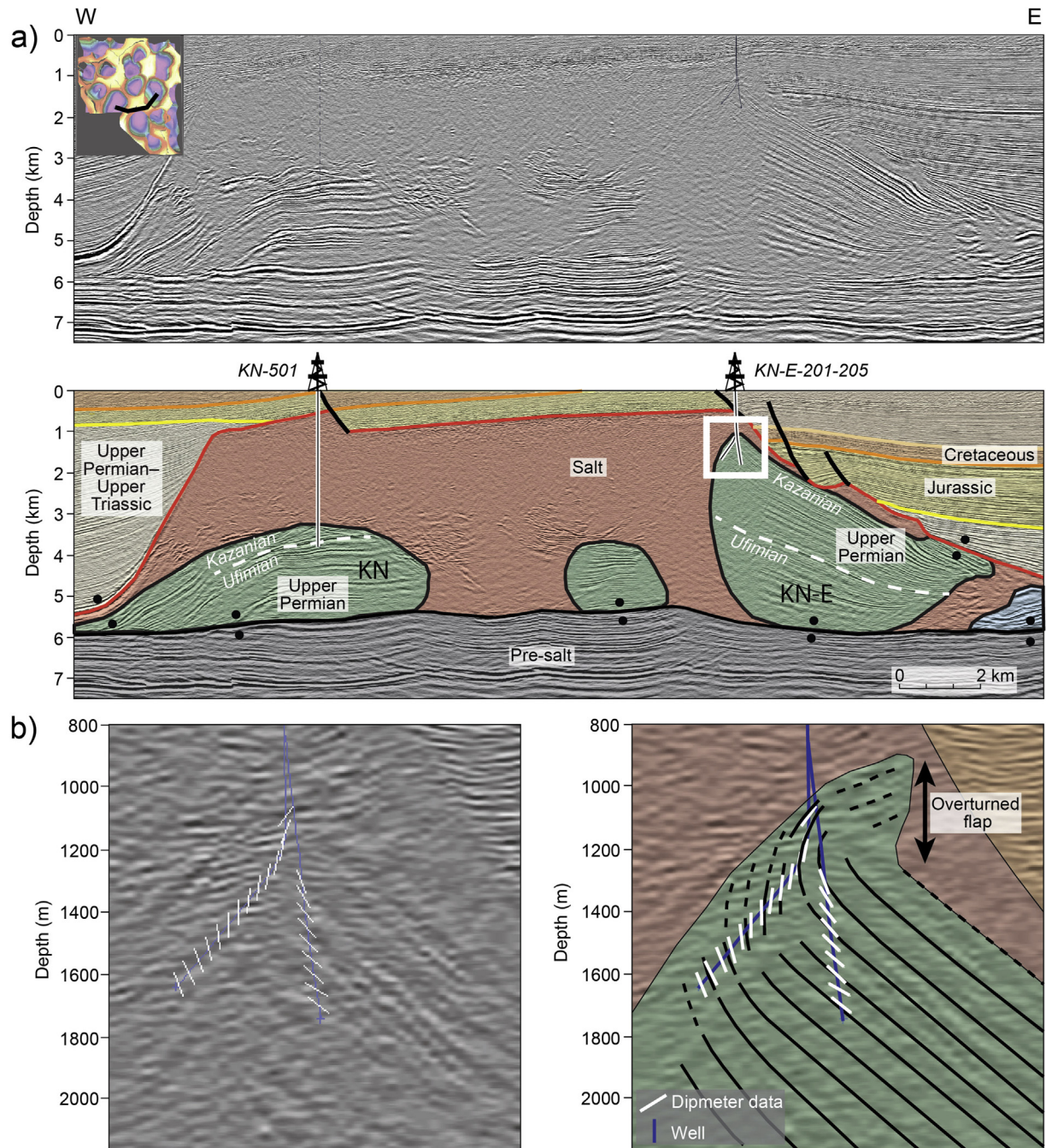


Fig. 11. a) Uninterpreted and interpreted seismic cross section illustrating the two enclosed minibasins (labelled KN and KN-E) that have been reached by drilling at KN-501 and KN-E-201-205 wells. Location of the wells, as well as the penetrated Kazanian–Ufimian boundary in the minibasin KN is indicated in the seismic section. In minibasin KN-E, the Kazanian–Ufimian boundary has been interpreted based on seismic facies correlation between the two minibasins. Location of the cross section is indicated in the inset map on the top left. b) Uninterpreted and interpreted detailed seismic section (white rectangle in (a)) of drilled apex of minibasin KN-E, showing the overturned flap.

encountered bedded evaporites. Furthermore, the presence of anhydrite at this stratigraphic level is consistent with the regional Upper Permian stratigraphy of the Precaspian Basin (Kukhtinov and Crasquin-Soleau, 1999; Barde et al., 2002b). The proportion of evaporite layers interbedded with the Ufimian and Kazanian clastic sediments in the suprasalt minibasins varies from one minibasin to another, from being almost completely absent, to 10 to 20 percent (Barde et al., 2002b), and locally between 30 and 50 percent (e.g., Karazhar South 1, which is located outside of the study area to the east; Preussag, 2003). Evaporitic rocks encountered in these wells are composed of halite, gypsum, and anhydrite. The empirical

depth-average density curve for siliciclastic sediments has been modified to illustrate the effect of increasing the amount (in percentage) of interbedded evaporites (Fig. 13b, c, and d). The estimated depth at which negative buoyancy occurs does not change when different percentages of halite are considered (Fig. 13b). However, small amounts of gypsum and anhydrite, both of which are denser than salt, can dramatically reduce the depth required for buoyancy inversion (Fig. 13c and d). Evaporites embedded with the undrilled siliciclastic sediments are most likely composed of varying amounts of halite, gypsum, and anhydrite. The depth at which buoyancy inversion occurs can be plotted on a ternary diagram that

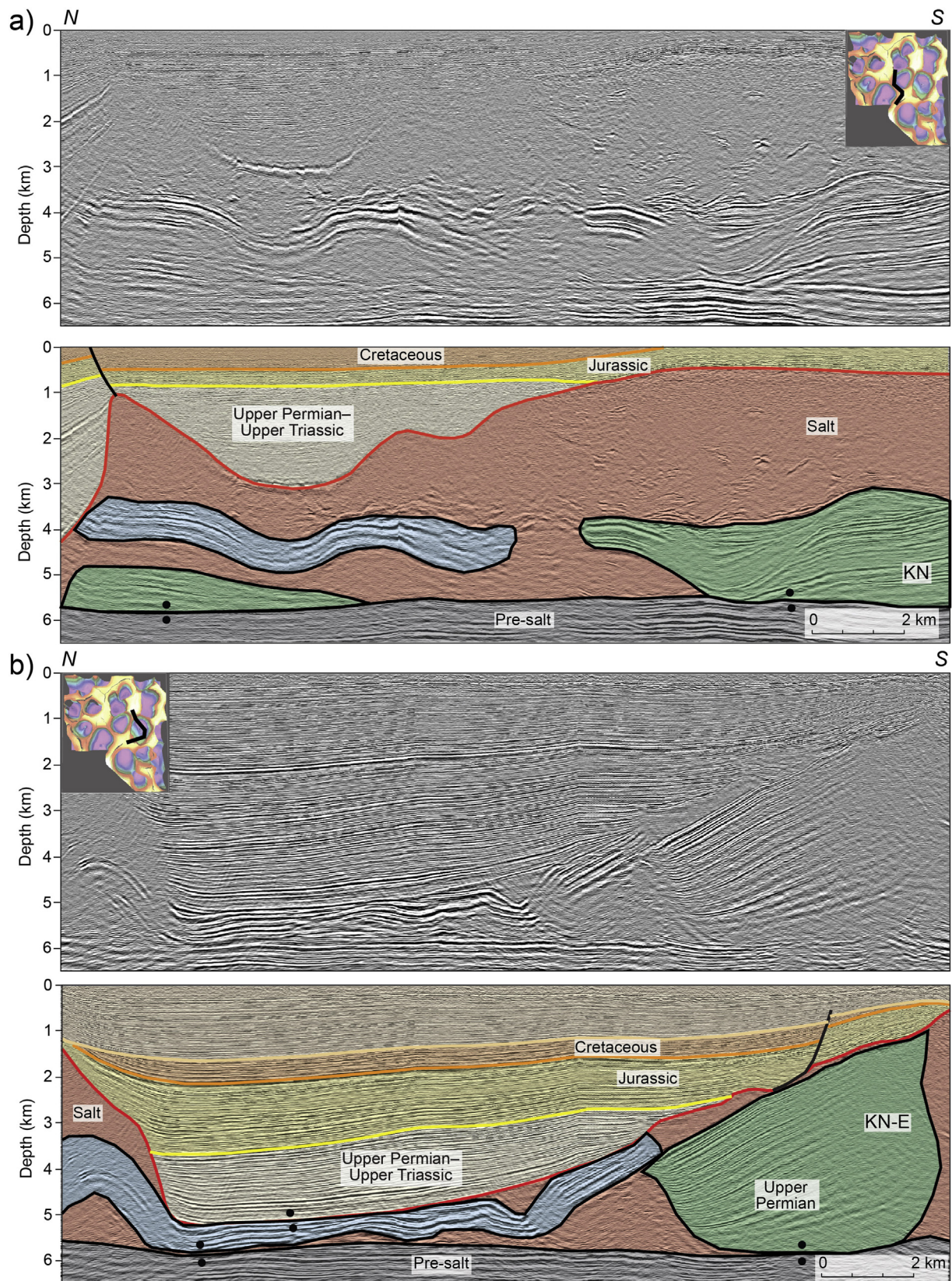


Fig. 12. Uninterpreted and interpreted seismic cross sections showing continuous tabular bodies and their relation with encased minibasins KN (a) and KN-E (b). Location of the cross sections is indicated on the top left and top right inset maps, respectively.

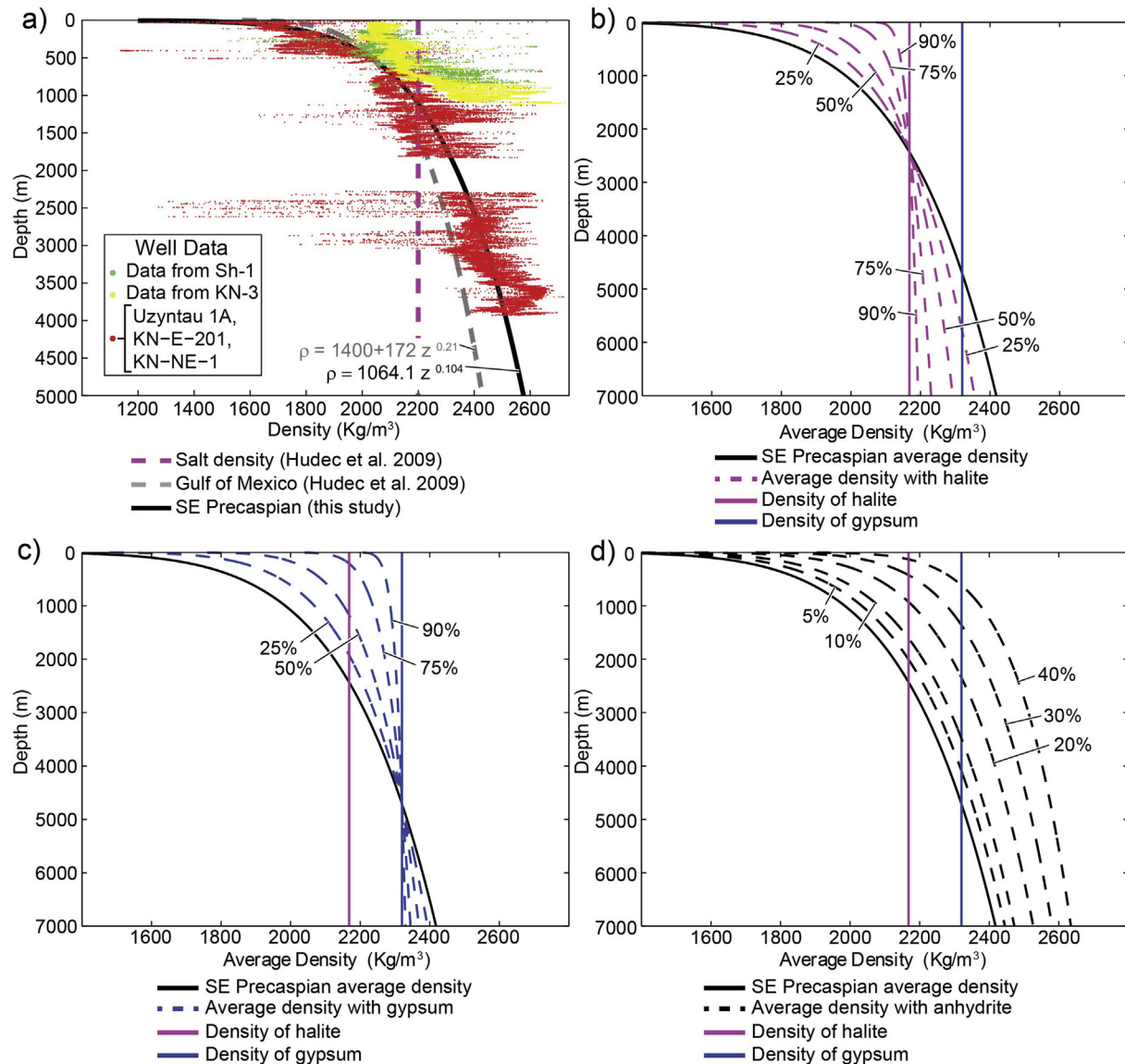


Fig. 13. a) Density-depth measurements from various wells. Data from three different wells (in red) were used to construct a density-depth curve for SE Precaspian. For comparison, density-depth curve constructed from well data in the Gulf of Mexico (Hudec et al., 2009), as well as the standard value of impure salt density, are shown. b) to d) Average density-depth curves for SE Precaspian for different percentages of interbedded evaporites. Interbedded evaporites used for the calculation are halite (b), gypsum (c), and anhydrite (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

considers the three different evaporites for a given percentage of the evaporites and clastic sediments (Fig. 14). Fig. 14 indicates, for example, that a section composed of 25% evaporites may become denser than halite after 1600 m of deposition (the thickness of most encased minibasins) if at least 35 percent of the evaporite content is anhydrite in a dual halite-anhydrite evaporite system.

5.2. Preferred model for minibasin encasement

Several observations argue against three of four of the minibasin-encasement mechanisms described in Section 3. First, the timing of encasement is different for the two encased minibasins that have been drilled, arguing against a single shortening event as a cause of encasement (Fig. 3b). Second, most encased minibasins are <2500 m thick (assumed original thickness of the salt in the area; Volozh et al., 2003), so were unlikely to have been welded to the base of salt at the time of encasement; Fig. 3c. Finally, the study area is not part of a suture zone between salt sheets or

canopies, so a suturing model (encasement by override by another allochthonous salt body; Fig. 3d) is not appropriate either. On the other hand, as already mentioned, the fact that all encased minibasins are welded to the base of salt argues that they are negatively buoyant, fulfilling the prime requirement for density-driven subsidence.

Even though density-driven encasement is the most likely mechanism to explain encasement of minibasins in the study area, alternative origins (such as encasement by salt expelled from beneath nearby minibasins, by salt expelled from shortened diapirs, or an intrasalt origin) cannot be completely discarded for the following reasons. First, the two thickest encased minibasins, which are both drilled, are both 2500- to 3000-m-thick, so both could have been welded to base of salt at the time of encasement. If so, they might have been overridden by salt expelled from beneath nearby suprasalt minibasins. However, the rest of the encased minibasins were much thinner when they were encased (Fig. 9), so were probably underlain by salt during encasement. Second, none

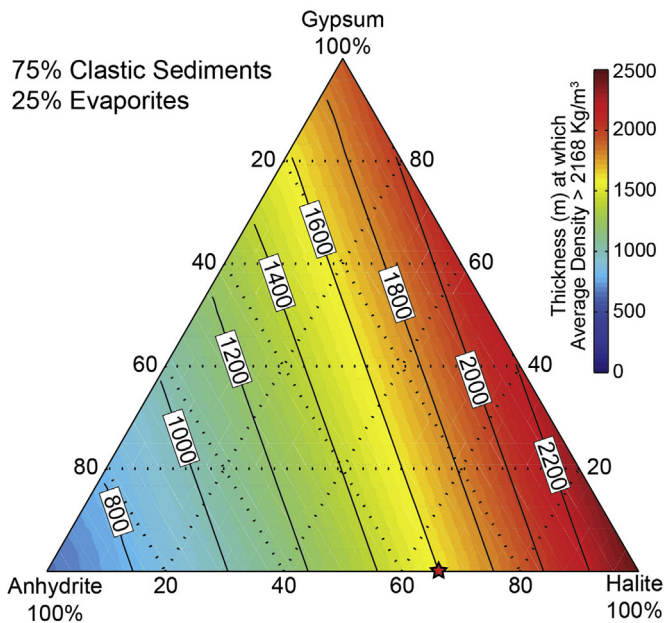


Fig. 14. Plot of the threshold depth/thickness (in meters) at which the average density of clastic sediments (following the empirical depth-density curve of SE Precaspian that includes 25 percent of evaporites) is higher than that of halite. The 25 percent of evaporites might be a combination of the three evaporites, halite, gypsum, and anhydrite. For example, with 25% of interbedded evaporites, a 1600 m-thick sediment sequence requires 65% of halite and 35% of anhydrite in a dual halite-anhydrite system to reach an average density higher than that of halite (point indicated by the star at the base of the triangle).

of the thinner encased minibasins have been drilled, so they may have originated as intrasalt sequences of layered evaporites. Third, shortening events associated with unconformities have been reported at the start of the Triassic, Jurassic, and Cretaceous, and during the Oligo-Miocene (Volozh et al., 2003) (Fig. 5). A Late Permian shortening event has not been documented, although the nearby Uralian orogeny was ongoing. Polyphase shortening events could conceivably explain the diachronous encasement of some minibasins.

5.2.1. Relation between suprasalt and encased minibasins

Most of the encased minibasins dip toward and/or are pinned below suprasalt minibasins. In one example from the Temir block in the eastern Precaspian Basin, an early minibasin, which is partially

overlain by a salt wing, forms a half turtle that dips toward a later depocenter to form a composite minibasin (Fig. 15; Barde et al., 2002b; Hudec and Jackson, 2011). If a continuous stratigraphic record was observed between the intrasalt and suprasalt minibasins developed in the ZW-1 block, they could conceivably represent similar composite minibasins. However, most of the intrasalt minibasins in the study area are either completely overlain by salt or show geometries typical of welds with overlying suprasalt minibasins rather than continuous stratigraphic records (Figs. 10 and 11).

We have no constraints on the age of the deepest parts of the suprasalt minibasins in the study area, so we cannot be sure if these relationships document younger minibasins that subsided onto older encased minibasins, or if they are equivalent-age sections juxtaposed by shortening.

5.3. Origin of tabular intrasalt packages

The absence of wells penetrating the intrasalt tabular packages in the study area and the subsequent lack of control on sediment age and lithology means these units may have formed in one of two ways. The first possibility is that they formed a layered intrasalt evaporite sequence originally interbedded within the Kungurian salt (Fig. 16). Alternatively, they may represent suprasalt sequences postdating the encased minibasins (Fig. 17a and b). In this section, we explore the feasibility of these two hypotheses. In either case, the original relationship between the encased minibasins and the intrasalt tabular packages was probably modified by shortening (Duffy et al., 2017) and the late-stage subsidence of the suprasalt minibasins.

5.3.1. Intrasalt origin

Three main arguments support an intrasalt depositional origin for the tabular packages. First, the seismic facies (high amplitude, low frequency) and deformational style (e.g., disharmonic folding between layers) of the packages suggest that they may be formed by layered evaporites with probably significant amounts of mobile halite. One obvious place to generate such a sequence is in the middle of a regional salt sequence, such as that represented by the Kungurian evaporites.

Second, intrasalt layers are known in other parts of the Precaspian Basin. In the northern and western parts of the basin, where the Kungurian salt is undisturbed, borehole data show up to 10 evaporite cycles, all of which contain layers of anhydrite, halite, sylvite, and magnesium salts (Anissimov and Moscovsky, 1998). Magnesium- and potassium-bearing salts have also locally been

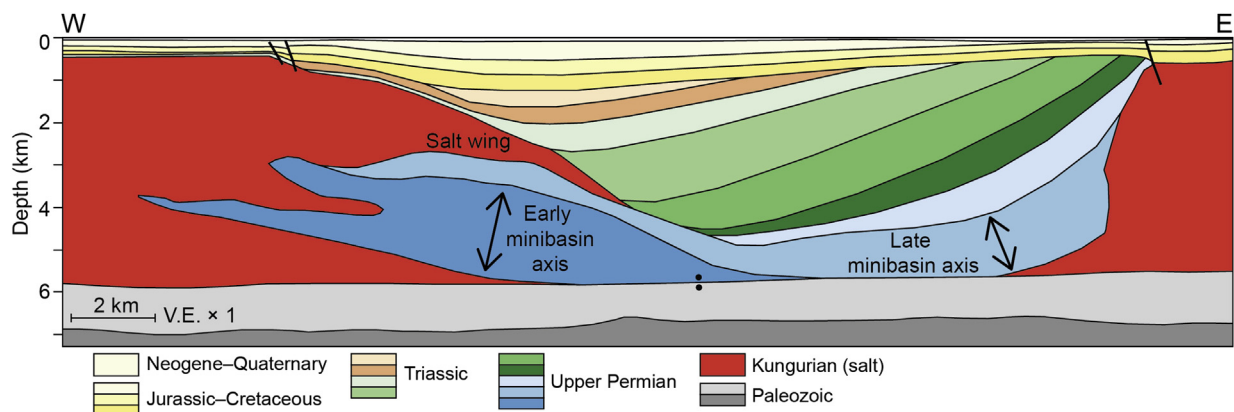


Fig. 15. Relation between an early minibasin and the overlying shifted depocenter in eastern Precaspian (Temir block). One early and one late minibasin axis are separated by a salt wing, forming a composite minibasin. The early minibasin is folded to form a half-turtle geometry that dips toward the late minibasin. Modified from Barde et al., 2002b.

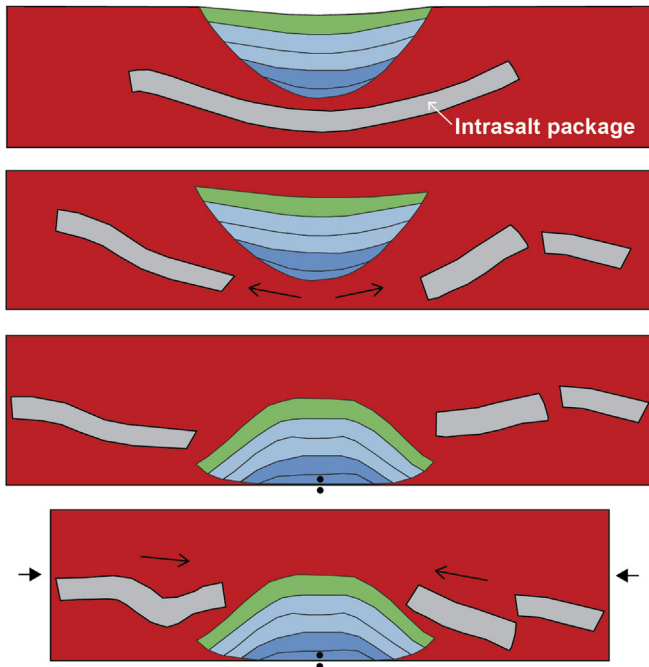


Fig. 16. Conceptual sketch of the origin and evolution of intrasalt of tabular bodies. The currently encased minibasins would cause initial lateral flow and expel the tabular packages from beneath them. Later shortening would cause further lateral salt flow and translation of tabular packages in the opposite direction. This reverse movement could explain the current position of the tabular intrasalt packages above the encased minibasins.

found in the central part and eastern part of the basin (Anissimov and Moscowsky, 1998).

Third, the internal layers in the tabular units maintain uniform thickness over long distances, consistent with the style of intrasalt layering in other basins (e.g., the Santos Basin, Jackson et al., 2014a; 2015). One place where this tabular-like geometry might occur in a suprasalt sequence is in condensed carapace sections over the rising diapirs. However, topographic highs above diapirs are the last places one would expect to see layered-evaporite deposition, given that the isolated water bodies needed to deposit halite would more likely form in flanking topographic lows (i.e., minibasins).

There are, however, several arguments against an intrasalt

origin for tabular packages. First, the tabular intrasalt bodies do not extend throughout the study area, but, rather, are clustered in the central part. Even if they were part of the same tabular body, their overall spatial extent is limited if compared with intrasalt sequences in other basins (e.g., Cartwright et al., 2012; Fiduk and Rowan, 2012; Jackson et al., 2014a, 2015). Second, in an intrasalt model, the presently encased minibasins would have begun as suprasalt minibasins, sinking onto the intrasalt tabular packages. Given this scenario, we would expect to see the tabular packages trapped beneath the encased minibasins. Instead, the observed tabular packages appear to be above the encased minibasins and not below. This would require the intrasalt tabular packages to flow outward with evacuating salt as the encased minibasins sank (Fig. 16). To gain their current position, the tabular packages would have had to either flow back in with salt above the sinking minibasin or be transported there during later diapir shortening. These scenarios are possible, but are not the simplest explanation.

5.3.2. Suprasalt origin

A single observation supports a suprasalt origin. Tabular packages tend to lie above the edges of encased minibasins where the two are juxtaposed (Fig. 12). The simplest explanation for this structural superposition is a stratigraphic superposition. If so, this would imply that the tabular packages represent suprasalt strata that accumulated evenly rather than forming a minibasin. Two scenarios can be considered for such tabular geometries. First, the tabular packages could have formed condensed sections (carapace) capping diapirs separating the earlier minibasins, but settled more slowly into the salt owing to their tabular geometry (Fig. 17a). Alternatively, the tabular packages could have formed isopachous, spatially limited sequences after minibasin subsidence and post-date minibasin welding (thick encased minibasin) or encasement (thin encased minibasins) (Fig. 17b).

Despite the structural superposition described above, there are several arguments against a suprasalt origin for tabular packages, most of which are corollaries of arguments favoring an intrasalt origin. Most obviously, it would be very difficult to interpret the tabular packages as supra-diapir carapace blocks if, in fact, they are composed largely of layered evaporites. Evaporites are much more likely to be deposited in low-lying minibasins flanking diapirs than above the crests of diapirs. Also, it would be problematic to encase large, flat-lying tabular packages with so little deformation because their aspect ratio must dramatically retard their sinking (e.g.,

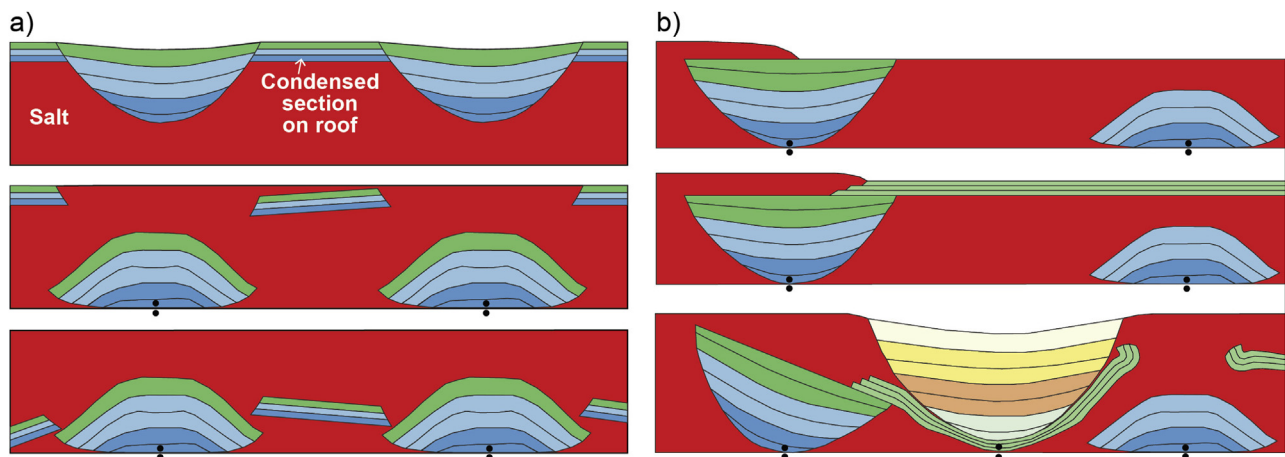


Fig. 17. Conceptual evolution sketches illustrating the two different scenarios under which tabular sedimentary packages originate above salt then become encased. a) Condensed section of roof is disrupted into slabs, which then sink. b) Roof sequence postdating encasement or welding of encased minibasins. In all cases, the late-stage subsidence of suprasalt minibasins could deform the tabular packages, which for simplicity is only sketched in (b).

Burchardt et al., 2012). However, because the tabular packages are welded at their base, where they appear pinned under the suprasalt minibasins, the suprasalt minibasins may have forced the tabular packages to reach the bottom of the salt (Fig. 17b).

6. General discussion and conclusions

The presence of more than 40 intrasalt sediment packages in the study area offers an opportunity to test criteria for the origin and evolution of these packages. We have identified two sets of sedimentary intrasalt inclusions: minibasins and tabular packages. On the basis of geometry and limited well control, the minibasins most likely formed above salt and were later encased. We lack well control for tabular packages, but, based on their geometry, apparent density, and deformation style, they likely originated as intrasalt or suprasalt layered-evaporite sequences. Both conclusions are tentative but illustrate how seismic observations can be used to infer the lithology and kinematic history of intrasalt sediments.

The abundance of encased minibasins in the southeastern Precaspian Basin suggests that some processes may be operating there that are not typical of salt basins in general. Why do some provinces have many encased minibasins and others none? We suggest that two factors should be considered. First, there must be some processes by which salt can be emplaced above the minibasin. These processes include density-driven subsidence, expulsion of salt from beneath nearby minibasins, shortening of adjacent diapirs, and override by other salt sheets. A second factor, less often considered, is that the minibasin must become separated from the rest of the suprasalt sequence. That is, the thinner overlying sediments that yoke minibasins together must be broken. We consider each of these factors here in the context of the southeastern Precaspian Basin.

Given that we interpret encasement in the study area to be a result of density-driven subsidence, minibasin buoyancy is obviously the key parameter. We infer that the abundance of depositional evaporites in the minibasins allowed them to achieve negative buoyancy while still quite thin and relatively uncompacted. Once negative buoyancy was achieved, all that minibasins needed to become encased was the disruption of the sediment bridges connecting the minibasins to one another across intervening diapirs. At least three factors may have contributed to this disruption. First, because evaporite-laden minibasins achieved negative buoyancy while thinner than normal, the interminibasin roofs would likewise have been thinner and weaker than normal. Second, the shallow-marine to nonmarine conditions that prevailed during the early part of basin history may have resulted in little or no sediment accumulating above the topographically high diapirs. Finally, any shortening propagating into the study area from the nearby orogenies would have squeezed the diapirs and disrupted their roofs. Given that the roofs in question are not preserved, we are unable to assess the relative importance of these factors.

Another aspect of intrasalt inclusions in the SE Precaspian is highlighted by the behavior of tabular sediment packages during later minibasin subsidence. Behavior of the tabular packages during subsidence of the encased minibasins is unclear owing to uncertainty in their relative ages. However, it is clear that the structure and location of the intrasalt tabular packages was profoundly influenced by subsidence of suprasalt minibasins. Tabular packages were locally pinned beneath the suprasalt minibasins, rotated and folded by salt being expelled from beneath the subsiding depocenters (e.g., Fig. 10). These patterns illustrate the complexity of salt flow in minibasin provinces and suggest that we can expect thinner, weaker inclusions in the salt to be highly deformed.

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