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Inversion tectonics: a brief petroleum industry perspective

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Abstract. The concept of structural inversion was introduced in the early 1980s. By definition, an inversion structure forms when a pre-existing extensional (or transtensional) fault controlling a hangingwall basin containing a syn-rift or passive fill sequence subsequently undergoes compression (or transpression) producing partial (or total) extrusion of the basin fill. Inverted structures provide traps for petroleum exploration, typically four-way structural closures. As to the degree of inversion, based on large number of worldwide examples seen in various basins, the most preferred petroleum exploration targets are mild to moderate inversional structures, defined by the location of the null-points. In these instances, the closures have a relatively small vertical amplitude, but simple in a map-view sense and well imaged on seismic reflection data. Also, the closures typically cluster above the extensional depocentres which tend to contain source rocks providing petroleum charge during and after the inversion. Cases for strong or total inversion are generally not that common and typically are not considered as ideal exploration prospects, mostly due to breaching and seismic imaging challenges associated with the trap(s) formed early on in the process of inversion. Also, migration may become tortuous due to the structural complexity or the source rock units may be uplifted above the hydrocarbon generation window effectively terminating the charge once the inversion occurred.

For any particular structure the evidence for inversion is typically provided by subsurface data sets such as reflection seismic and well data. However, in many cases the deeper segments of the structure are either poorly imaged by the seismic data and/or have not been penetrated by exploration wells. In these cases the interpretation of any given structure in terms of inversion has to rely on the regional understanding of the basin evolution with evidence for an early phase of substantial crustal extension by normal faulting.

1 Introduction

Whereas the concept of structural inversion has been around for a century (e.g. Lamplugh, 1919), the term has been specifically used for the first time by Glennie and Boegner (1981) to explain the evolution of the Sole Pit structure located in the UK sector of the southern North Sea. The first generalized description of structural inversion was offered by Bally (1984)

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using a 3-step cartoon depicting an extensional half-graben subjected to subsequent contraction. Both the concept and the term of inversion tectonics gained rapid acceptance by the petroleum industry and the academia as shown by the large number of papers produced about this subject in the 1980s and 90s (Cooper et al., 1989; Buchanan and Buchanan, 1995).

In this paper we provide a brief overview of inversion tectonics, specifically from the view point of the petroleum industry. The last 30 years saw lots of work done on the practical application of this important structural geology concept in the hydrocarbon exploration process. Whereas the impact of structural inversion became increasingly evident in many case studies, in our opinion, there is room for improvement in two major aspects. Firstly, the term of structural inversion is being used in a very broad sense across the industry which underlines the need to revisit the original definition of this process. There has to be a clear distinction between regional-scale and individual structure (prospect)-specific inversion as these processes manifest themselves differently. Secondly, we observe an interesting disparity in the usage of structural inversion in the petroleum industry. During the life-cycle of many exploration and production projects the interpretation of the trap(s) in terms of structural inversion is preferentially used during the exploration phase as it has, in general, a positive connotation for prospectivity (see later). In contrast, during the appraisal and production phase the interpretation of the traps in a field in terms of inversion, as a trap forming mechanism, typically becomes un(der)appreciated. We found that the description of existing fields generally lacks the reference to inversion tectonics as the trap forming mechanism, but instead, the trap itself is referred to as the result of reverse faulting or compression.

We provide below two case studies of regional-scale and prospect/field-scale structural inversion to illustrate the typical challenges of applying this important concept in the petroleum industry. We chose two hydrocarbon fields from two very different basins to illustrate various aspects of the interpretational process of invoking inversion for the traps in these fields. The Lovászi oil/gas field in the Pannonian Basin of Hungary is an onshore field which was discovered in 1940 and it is already depleted (e.g. Dank, 1985). The giant offshore Tamar gas field in the Israeli sector of the Levant Basin was discovered in 2009 and it started to produce just recently (Needham et al., 2017). Whereas there are major differences between these fields, they are similar in the sense that their inverted nature may not be clearly determined by analysing them in isolation, but only in a regional geologic context. Therefore we will zoom out from the areas of these hydrocarbon fields and will highlight the regional aspects of the inversion in the respective basins where they are located.

Finally, we offer a brief overview of the multi-faceted impact of structural inversion on the petroleum systems as it is of paramount importance for hydrocarbon prospecting. As an outlook, we emphasize the need for a more quantitative and systematic description of inverted structures worldwide. The statistically driven data-mining approach, establishing observationally the most optimal degree of structural inversion, appears to be missing to date, at least in the public domain publications.

2 An unpublished cartoon on inversion tectonics by Albert W. Bally

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The first generalized description of structural inversion was offered by Bally (1984) using a cartoon depicting the evolution of an extensional half-graben subjected to subsequent contraction in three steps. Interestingly, we have found an unpublished extended version of Bally's original inversion model which he designed during the early 2000s at Rice University to show the progression of inversion into the formation of an incipient folded belt (Fig. 1). Specifically, he made this cartoon to illustrate the development of the western Atlas in Morocco. Whereas the inversion at the western termination of the Atlas system has already been described by Hafid et al (2006), we felt that it is proper to reproduce in this Special Issue of Solid Earth Bally's own schematic summary of inversion tectonics which was left out from that paper (Fig. 1). Importantly, in this unpublished version he added some new elements to his original visual summary (Bally, 1984). In the description of this cartoon summary below we also use some of his unpublished text.

The term inversion tectonics should in our view be restricted to situations where extensional and/or transtensional systems are inverted to form inversion anticlines. Figure 1 is based partially on an earlier illustration by Bally (1984) and attempts to sum up the main characteristics of these systems. During the extensional phase, stratal geometries vary between two end-members depending on the relative rates of sedimentation versus horizontal extension (Fig. 1b and c). Rates of sedimentation which keep up with the extension lead to the familiar growth pattern in the graben with characteristic updip convergent strata. In contrast, when sedimentation rates lag behind the extension rates it will result in the subhorizontal infill of the half-grabens.

Minor (or mini) inversions involve partial inversion of the graben fill (Fig. 1d) which could be difficult to differentiate from forced folds (e.g. Withjack et al., 1990) associated with extensional tectonics. The inversion can proceed until the extensional system is restored to its pre-kinematic configuration, reaching the null-point (Fig. 1d). s*ensu* Williams et al. (1989). As inversion further advances, essentially co-planar reverse faults and/or short-cut faults may form. Minor subsidiary décollement systems will eventually appear on the flanks of the uplifts as the stresses are transmitted along the competent strata of the foreland adjacent to both sides of the inversion system.

On seismic reflection profiles inversion structures are characterized by thick asymmetrical anticlinal cores representing the extensional regime and updip thinning flanks that represent the inversion regime. The later updip convergence sequence is most prominent over the maximum graben fill (Fig. 1e) and thus differs from the updip convergence associated with the earlier extensional phase (Fig. 1b). The inversion sequence provides timing constraints for the inversion phase but because of its high position on the structure it is frequently eroded (Fig. 1f).

3 A worldwide data base on petroleum fields: reported cases of inversion tectonics

To determine to what degree structural inversion is understood and recognized in the process of exploration, development and production of hydrocarbons we decided to conduct a data mining exercise. In petroleum industry practice, the traps of producing reservoir units in hydrocarbon fields are always specifically described as it provides critical information.

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We had access to a very large, almost worldwide (excluding onshore US and Canada) comprehensive data base on hydrocarbon fields and discoveries (IHS Markit, 2020). This data base differentiates between the "trap form type" described in any given field (like "reverse fault" or "thrust") and the "trap forming mechanism" (like "compression" or "inversion"). Obviously, the trap form type is a simpler, observational category compared to the trap forming mechanism which is a more complex, interpretational category.

A query for the word "inversion" under the trap forming mechanism in this huge worldwide data base (IHS Markit, 2020), containing detailed information on about 31,000 fields and discoveries with about 70,000 reservoir units, provided 720 field and about 2,000 reservoir unit matches. Interestingly, this means that only about 2.3% of the fields were classified under the “trap forming mechanism” as inversion. On the level of individual reservoir units within all the hydrocarbon fields worldwide, the corresponding number is 1.7%.

Another data base query on circa 2,000 reservoirs, worldwide (excluding onshore US and Canada) classified as “reverse fault” or “thrust fault” in the trap form type provided only about 60 matches for inversion as a trap forming mechanism. This translates to about 3%, again, a very low proportion of the reported cases (Fig. 2). We believe that these low percentages for reported inversion tectonics in hydrocarbon fields and their reservoir units might be related to the fact that detailed trap descriptions are always difficult to obtain from the operators of these fields. Moreover, the relevant information for the correct classification and reporting is rarely available in publications.

Therefore we believe that during the life-cycle of many exploration, appraisal, development and production projects the term "inversion" is often used quite loosely during the initial exploration and appraisal phase. In contrast, during the development and production phase the exact meaning of inversion as a trap forming mechanism many times becomes irrelevant and it is replaced in the reporting practice by the more generic "compression" or "overthrusting" descriptors. With other words, whereas inversion tectonics appears to be somewhat overrated in exploration, it is quite possibly underreported in production projects.

Another important consideration is the fact that structural inversion has become well known only since the 1980s. Therefore, the traps of many hydrocarbon fields discovered before have been already classified as the result of simple compression or overthrusting. One of the examples we discuss below, a large onshore oil and gas field discovered in Hungary in 1940, clearly illustrates this situation. The trap of the Lovászi field has been traditionally described as a compressional anticline in keeping with the structural observations made long before the advent of inversion tectonics.

4 A case study from the Pannonian Basin, Hungary: Lovászi oil and gas field

Large, but subtle surface anticlines were known in the western Pannonian Basin for a long time (Fig. 3), referred to as the “Sava Folds” after a local river crossing the border zone between Hungary, Slovenia and Croatia (Stille, 1924). Based on the regional compilation of vertically exaggerated composite seismic lines in this area, Tari (1994) found many cases for very young, in many cases ongoing, uplift of the pre-Cenozoic basement from below the Neogene basin fill. This upwarping

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occurs on different wavelengths (Fig. 4). The small features include local folding and/or thrusting of the post-tectonic cover with the inversion of syn-rift structures. Whereas these Sava Folds have map-view dimensions on the scale of 10s of kilometers, there are much larger scale neotectonic uplifts in the Pannonian Basin (Fig. 4). In particular, the Transdanubian Range of western Hungary experienced significant neotectonic uplift and exhumation during the Quaternary, with a wavelength of about 100 km. Tari (1994) distinguished these two end-member categories of uplift with different wavelength and, for the first time, attributed them to regional-scale and local-scale inversion tectonics. Especially, the map-view of the smaller-scale inverted structures (Fig. 3) suggests that the inversion and uplift are propagating into the intra-Carpathian region from the W (Tari, 1994). Indeed, in-situ stress measurements showed compressive stresses in the western part of the Pannonian Basin, while tensile stresses were obtained in the eastern part (e.g. Dövényi and Horváth, 1990).

On the scale of the entire Pannonian Basin, the inverted structures are concentrated at the western margin of the basin gradually propagating eastwards into the basin since the Late Pliocene. The inversions are driven by the ongoing shortening in the broader area, including the Alps, between the Adriatic promontory of Africa and the European plate (Tari, 1994; Horvath, 1995; Horvath and Tari, 1999; Bada et al., 1999, 2007; Tomljenovic and Csontos, 2001; Horvath et al., 2006; Cloetingh et al., 2006). As another contributing factor to neotectonic inversion, Bada et al. (2001) analysed the role of topography-induced gravitational stress in basin inversion in the Pannonian Basin. They found that the kinematics of the inversion of the western Pannonian Basin is consistent with topography-induced gravitational stress which locally exceeds the magnitude of the far-field stress (Bada et al., 2001).

4. 1 The Budafa field

The Sava Folds, recognized as early as 1919 (Stille, 1924), almost exactly a century ago, offered obvious drilling targets for hydrocarbon exploration (e.g. Dank, 1985). The breakthrough came in 1937 when the Budafa anticline was drilled (Fig. 5). The Budafa field was the first significant discovery during the hydrocarbon prospecting efforts in post-war Hungary (e.g. Tari and Berczi, 2018). The Upper Pliocene (Pannonian) beds outcrop on the surface with dips between 3-10° defining an anticlinal four-way closure of about 18-20 km^2. Subsequent appraisal and development drilling established the multiple oil and gas reservoir units within the lower Pannonian part of an east-west striking folded anticline at 900 to 1300 m depth. The 2D vintage reflection seismic illustration of the Budafa field (Fig. 5) is orientedperpendicular to the fold axis. It shows the asymmetric nature of the anticline suggesting an underlying master fault on the northern flank of the structure. Even on this moderate quality vintage line acquired in the early 1980s one can interpret the thickening of the Upper-Middle Miocene (“Sarmatian-Tortonian-Helvetian”) strata beneath the apex of the anticline providing evidence for the latest Pliocene to Quaternary inversion of a Miocene syn-rift graben However, the seismic data quality is not good enough the properly delineate the position of the master fault, let alone that of the null-point.

4. 2 The Lovászi field

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We chose another example of the Sava Folds which provided an important oil and gas find in the region. One of the first major oil fields discovered in Hungary, Lovászi, is also an inverted anticline delineated by potential field data and surface dip measurements in the western Pannonian Basin in 1940. As this particular exploration play was relatively simple, i.e. E-W trending anticlines with relatively shallow Pliocene to Miocene clastic reservoir targets, all the prospects of this play were drilled up as early as in the 1940's (Dank, 1985) and most of them are essentially depleted by now.

Based on abundant well control, the Pliocene to Miocene succession in the broader area was studied by Juhász (1994, 1998). Her sub-regional lithostratigraphic transect, crossing the Lovászi field (Fig. 6), clearly shows a prominent surface anticline with a vertical relief of about 800-1000 m associated with the Pliocene to Upper Miocene (Pannonian; Sarmatian to Badenian) strata compared to their regional levels in this part of the Pannonian Basin. The Lovászi anticline is depicted as a slightly asymmetric one, therefore, in our interpretation, suggesting an underlying master syn-rift fault on its southern flank (Fig. 6). However, given the lack of deep wells penetrating the entire syn-rift core of the inverted anticline, the geometry of the inferred master fault and the location of a null-point along it cannot be established using well data only.

As there is modern 3D seismic data available covering the entire Lovászi field (Tóth and Tari, 2014) the structural history of this anticline can be studied in the context of its inverted nature (Fig. 7). The interpretation of the seismic data (Fig. 7a) reveals the growth of anticline in the manner depicted in Bally's cartoon (Fig. 1). In particular, the thickening/thinning geometries within the Upper Pliocene (Pannonian) strata in the apex of the anticline show the switch from extension to compression (Fig. 7a). Interestingly, flattening on multiple seismic horizons demonstrated the early growth of the anticline during the early Pannonian already focusing hydrocarbon migration into the structure (Tóth and Tari, 2014). The main period for the formation of the anticline, however, is clearly post-Pannonian as all the Pannonian reservoirs levels are gently folded (Fig. 7c) into low-amplitude 4-way closures (Fig. 7b).

Historical production from the multiple Pannonian reservoirs of the Lovászi field (Fig. 7c) was about 50 mmbbl oil and 230 bcf gas. Current exploration efforts are focusing on the deeper parts of these anticlines where reservoir quality prediction and imaging of viable traps are the main challenges (Tóth and Tari, 2014). As most of these anticlines are the products of Late Pannonian (Pliocene) to Quaternary inversion of Middle Miocene syn-rift half-grabens, the proper structural understanding of the core of the anticlines is critical for any future exploration efforts.

5 A case study from the East Med: Tamar gas field

Another region where inverted anticlines have been described is located in the Eastern Mediterranean (Fig. 8). These Syrian Arc structures, as named by Krenkel (1925), extend from the Sinai to the Palmyrides with a typical trend of ENE-WSW to NNE-SSW. These prominent features formed by the inversion of pre-existing Mesozoic extensional structures from the late Cretaceous to Oligocene times. Two main phases of folding have been documented so far (e.g. Walley, 1998). The first one can be dated as an intra-Santonian phase of deformation (early Syrian Arc phase) and the second one is dated dominantly as a late Eocene series of events (late Syrian Arc phase).

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From an exploration point of view, the Syrian Arc structures are very important. For example, the traps within several onshore Egyptian hydrocarbon fields are formed by Syrian Arc events (e.g. Dolson, 2003). Also, Middle to Late Cenozoic Syrian Arc style compressional features are present in the deepwater of the Eastern Mediterranean providing the traps for many deepwater discoveries during the last decade (e.g. Gardosh and Tannenbaum, 2014).

It is important to emphasize, that not all Syrian Arc anticlines are basement-involved structures and therefore, not all of them are inverted features in the strict sense of the word (e.g. Cooper et al., 1989). A regional Upper Triassic salt sequence provided an effective detachment surface for numerous anticlines in the Damascene segment of the Arc in Syria(Fig. 8).

In northern Egypt (Fig. 8), sedimentation during the Late Cretaceous was interrupted during the Santonian by the development of inversion-related folds across (Moustafa, 1988; Sultan and Halim, 1988; Guiraud and Bosworth, 1997; Bosworth et al., 2008). The Egyptian Syrian-Arc extends from the Western Desert to the Northern Sinai (Fig. 8). The Syrian Arc inverted anticlines have been described from the subsurface and using outcrop studies in the western Desert (Yousef et al., 2019), west of Cairo (Moustafa, 1988), in the Eastern Desert (Moustafa and Khalil, 1995) and in the northern Sinai (Moustafa and Khalil, 1989; Yousef et al., 2010). The formation of the Syrian-Arc has been attributed by Guiraud and Bosworth (1997) to changes in the Africa–Arabia plate motion with respect to the Eurasian plate at the end of the Santonian.

In Israel and Palestine, mostly subsurface data suggest that many of the Syrian Arc structures are in fact associated with the reverse reactivation of pre-existing Triassic and Jurassic normal faults (Freund et al., 1975; Druckman et al., 1995). Contraction started in the latest Cretaceous and continued through the Neogene (Eyal and Reches, 1983; Eyal, 1996; Walley, 1998). Just like on the regional scale, two periods of inversion tectonics were documented using reflection seismic and well data. An earlier phase of Senonian to Eocene inversion was followed by a later phase in the Miocene (Gardosh and Druckman, 2006). Interestingly, early Syrian Arc phase (Syrian Arc I) inverted structures are mostly located onshore and in the narrow shelf area of the Levantine Basin (Figure 9). Most of these thrust fault controlled structures are asymmetric anticlines with high-amplitude and short wave-length (Gardosh and Tannenbaum, 2014). In contrast, the inverted anticlines of the late Syrian Arc phase (Syrian Arc II) are found in the offshore part the Levantine Basin (Fig. 9). These structures are subtle, having a generally low-amplitude, but large map-view closure (Gardosh and Tannenbaum, 2014). They also appear as almost symmetric folds which were still active during the Messinian (see later).

5.1 An inverted "Syrian Arc I" structure in Egypt: the Mango discovery

As a subsurface example of a typical Syrian Arc inverted anticline, we chose an offshore Sinai structure in Egypt. The Mango structure (Fig. 10) is a circa 24 km long, WSW-ENE oriented anticline with relatively steeper dips on its northwestern flank (Yousef et al., 2010). After an initial oil discovery drilled on the structure, two more appraisal wells have been drilled to test the potential of the Lower Cretaceous clastic sequence in this inverted structure. The thickening-thinning relationships within the Mesozoic-Cenozoic sequence define a Jurassic to Early Cretaceous period of normal faulting along a poorly imaged master fault (Fig. 10). In contrast, the overlying mostly Cenozoic sequence displays progressive onlap

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onto the apex of the anticline. The Mango doubly plunging anticline, is just one of the many other Syrian Arc inverted structures in the offshore North Sinai with a characteristic ENE to NE strike (Fig. 9).

5.2 An inverted "Syrian Arc II" structure in Israel: the Tamar gas field

The giant Tamar field, with its 7-8 tcf biogenic gas reserves, is located in deepwater Israel (Fig. 9) and it was discovered in 2009 (Needham et al., 2017). On a depth-converted regional seismic section (Fig. 11a) the Tamar structure is a very prominent anticlinal feature mostly pre-dating the overlying Messinian evaporite sequence. In map-view (Fig. 11b) the Tamar anticline has a slightly asymmetric closure trending SW-NE. The prominent NW-SE striking "piano-key" faults (Kosi et al., 2012) cross-cutting the anticline are quite typical for the entire deepwater Levant Basin. These faults are not sealing in nature as the GWC is at the same depth of 4797 m (Fig. 11b) across the entire Tamar gas field (Needham et al., 2017). A dip-oriented section we have constructed across the Tamar field assumes the isopachous nature of the three main reservoir intervals (Sand A, B and C) reported by Needham et al. (2017) and it reveals the subtle asymmetry of the structure (Fig. 11c). The slightly steeper SE flank of the anticline suggests an underlying master fault, yet, the regional-scale seismic section (Fig. 11a) does not display such a fault anywhere down within the Cenozoic sequence. Similarly to the Lovászi field discussed earlier (Fig. 7), the reservoirs of the Tamar field are located stratigraphically fairly high within the structure, in the post-rift sequence. These Miocene reservoirs are located in an isopachous sequence which deposited before the inversion took place (Fig. 11c). Since the Mesozoic (Jurassic-Early Cretaceous?) master fault responsible for the inversion is located a few kilometers beneath the Tamar anticline its geometry is poorly defined by the seismic data (Fig. 11a). The existence of a Mesozoic syn-rift graben at depth is mostly supported by the analogy with the much better imaged and understood Syrian Arc structures located closer to the coastline (Gardosh et al., 2008; 2010, 2011; Gardosh and Tannenbaum, 2014).

6 The impact of inversion tectonics on petroleum systems and exploration efforts

Whereas there are lots of publications are devoted to the structural geology of inversion, there are only a few papers which tried to generalize the impact of inversion tectonics on petroleum systems (e.g. Macgregor, 1995; Turner and Williams, 2004; Cooper and Warren, 2010; Bevan and Moustafa, 2012). Looking at Bally's cartoon (Fig. 1) it is intuitive to assume that there has to be a "Goldilocks Zone" of inversion tectonics from a petroleum exploration point of view. However, this optimum is not simply the function of the trap size but also the function of the complex interaction between the source, reservoir and seal rocks via hydrocarbon migration.

From a strictly petroleum systems point of view the positive connotation of inversion tectonics in the petroleum industry is largely due to the trap and the reservoir development, i.e. robust closures with reservoirs in them as the syn-rift basin fill tends to accumulate reservoirs. In contrast, the negative connotation of inversion tectonics is based on its perceived impact on the charging and sealing, i.e. the uplift shuts down the generation in the syn-rift source kitchen and the ongoing deformation tends to lead to breaching and exhumation.

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The summary below is largely based on the work of Bevan and Moustafa (2012) who used the examples of three onshore Egyptian fields (e.g. Razzak, Mubarak and Kattaniya) to generalize some observations. We note that these cases specifically capture the learnings from inverted structures in a failed wide rift setting in an onshore basin where the post-rift basin fill is very thin, especially compared to the syn-rift sequence (Fig. 12).

Inversion structures which are relatively mild develop low-amplitude but robust 4-way closures in the hangingwall of the master fault responsible for the structure (Fig. 12a). The master fault does not necessarily have to manifest itself at the level of the reservoirs. As described earlier in the case of the Lovászi and Tamar fields inverted structures could have large closures higher up in the unfaulted sequence (Figs. 7 and 11, respectively). As to charge, the position of source and seal rocks in the hangingwall side of the fault is quite critical. Whereas the source rocks located beneath the inverted anticline may actually migrate away from the structure, the source rocks on the flank of the footwall may generate hydrocarbons which then migrate to the tip of footwall and travel along the fault to the ultimate trap in the apex (Fig. 12a).

In the more advanced inverted structure (Fig. 12b) the same basic charge limitation occurs, i.e. the majority of mature hydrocarbons from within the source rocks within the deeper syn-rift sequence will migrate away from the hangingwall closure associated with the reactivation of the master fault. However, the smaller closures that could develop above antithetic faults on the subsidiary side of the half-graben (Fig. 1e) may receive charge (Fig. 12b). This asymmetric arrangement of traps associated with near null-point inversion is informally called the butterfly structure (see Fig. 1e).

In the most advanced cases of structural inversions (Fig. 12c), the reservoir units in the hangingwall become uptilted and potentially exposed on the paleo-surface, therefore becoming breached. As noted by many, the vertical uplift of source rocks, potentially generating hydrocarbons prior to the inversion, may switch off the kitchen as the source rocks may reach shallower depth where they are not generating any more (e.g. Turner and Williams, 2004; Cooper and Warren, 2010). In these more severe cases of inversion, the smaller, subsidiary structures on the flank should be targeted (Fig. 12c). These smaller closures may remain unbreached and could receive charge from downdip source rocks as Bevan and Moustafa (2012) pointed out.

As to the regional scale impact of structural inversion we would like to highlight here the simple point made by Tari and Jabour (2011). The large gas discoveries of the last decade in the deepwater Levant Basin are all associated with inverted structures which strike parallel with the margin (Fig. 10). From a trapping point of view this translates to an optimum situation as the closures of the four-way anticlines are not significantly affected by the regional basinward dip trending perpendicular to the anticlinal axes (Fig. 13). In contrast, on passive margin where the inversional anticlines have the same trend as the regional dip, the four-way closures on the updip end of the structures tend to be much smaller (Fig. 13). Late Cenozoic to Recent inversion and uplift of the Atlas system, as the result of African-Eurasian plate convergence, is well documented in the onshore Essaouira Basin and the western High Atlas of Morocco. However, various 2D and 3D seismic reflection data sets acquired in the offshore Essaouira-Safi segment of the Atlantic margin of Morocco also show the presence of similar compressional structures in the deepwater area as well (e.g. Hafid et al., 2006; Tari and Jabour, 2013). These prominent structures are best imaged outboard of the widespread salt basin, some 200 km to the west from the

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coastline, in water depth of 2,000-4,000 m. The anticlines have a general WNW-ESE trend, perpendicular to the overall strike of the Central Atlantic margin, but parallel with the regional dip of the margin. Therefore we believe that the regional-scale trend of the inverted structures versus the regional dip in a passive continental margin or in a foredeep setting is quite important (Tari and Jabour, 2011).

7 Discussion and outlook

Whereas inversion tectonics could produce spectacular traps, inversion tectonics is a process which has profound implications on other elements of the petroleum systems and, therefore, the prospectivity, both in a positive and a negative sense (e.g. Macgregor, 1995; Turner and Williams, 2004; Cooper and Warren, 2010). The most negative impact is attributed to the fact that during inversion source-rock sections are brought much closer to the paleo-surface and therefore previous mature source-rocks switch-off and become non-generative. Also, the main reservoir and source-rock sections are many times being brought to the surface and therefore breached. There are many other negative, but valid impacts listed by Turner and Williams (2004) giving the impression that inverted features may be more challenging for exploration than "regular" anticlines formed by simple contraction. Perhaps, their view might also somewhat biased by considering examples from exhumed European Atlantic margins (e.g. Dore et al., 2002). In these regionally inverted rifts basins there are plenty of evidence for underfilled fields and former petroleum accumulations which were breached and leaked away due to inversion tectonics (Turner and Williams, 2004).

Yet, in many other basins of the world, inverted structures provided repeatable and highly successful plays. In particular, the examples we chose for this paper located in the Sava Folds region of the western Pannonian Basin and the Syrian Arc anticlines in the deepwater Eastern Mediterranean basin turned out to be very successful, especially in the Levant.

We believe that the key for the success in these basins is that source rocks are not constrained to the extensional basin fill but rather occupy a higher, but pre-inversion stratigraphic position. These source rocks tend to be unconfined to the underlying extensional basins and more regional in character. Indeed, as Bevan and Moustafa (2012) already noted, in contrast to the syn-rift sequences, as post-rift kitchens tend to lie in the synclines between inversion anticlines, such that lateral migration is generally toward the anticlinal axes. These structures can therefore be more successful at shallower reservoir levels. Given the position of the active source rock sequences in the post-rift basin fill in our examples, the hydrocarbon generation could be assumed regionally and the inverted anticlines becomes the focus of the ongoing charge, see the examples of both the Lovászi and Tamar fields (Figs. 7 and 11, respectively).The other element of the sometimes negative perception of inversion is the fact that there are not that many successful examples described globally. Again, only about 3% of the traps of hydrocarbon fields with reverse faulting or overthrusting are associated with inversion in the reporting practice cases (Fig. 2). We believe that this number should be significantly higher as many inverted structures may not be recognized as such.

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Finally, we would like to emphasize the need to better quantify the degree of inversion for any given structure in order to find the optimum trapping situation for exploration efforts on a global scale. With other words, what degree of inversion provided the largest number of HC fields worldwide?

However, this analysis requires a quantitative description of the inversion. There are two ways of doing this (Fig. 14). Williams et al. (1989) introduced the concept of inversion rate, i.e. the magnitude of contraction due to inversion versus the magnitude of extension. In seismic profiles, this is equivalent to the ratio between the thickness of syn-rift deposits above the null point parallel to the fault plane and the total thickness of syn-rift deposits parallel to the fault plane on the hanging-wall (Fig. 14a). However, the inversion rate may be difficult to calculate in cases when the null-point cannot be located with confidence. An alternative method was proposed by Song (1997) to calculate the inversion rate (Fig. 14b), but this method also requires good handle on many elements of the stratal geometry along the master fault (e.g. Yang et al., 2011). In our opinion, the quantification of inversion degree is a challenge as the deeper section beneath an inverted anticline is typically not well imaged seismically and/or not drilled due to the greater depth. The inversion rate in both of the case studies described in this paper, i.e. Lovászi and Tamar fields (Figs. 7 and 11, respectively) would be difficult to determine, at best.

8 Conclusions

Inverted structures provide traps for petroleum exploration, typically four-way structural closures. As to the degree of inversion, based on large number of worldwide examples seen in various basins, the most preferred petroleum exploration targets are mild to moderate inversional structures. In these instances, the closures have a relatively small vertical amplitude, but simple in a map-view sense and well imaged on seismic reflection data. Also, the closures typically cluster above the extensional depocentres which tend to contain source rocks providing petroleum charge during and after the inversion. Cases for strong or total inversion are generally not that common and typically are not considered as ideal exploration prospects, mostly due to breaching and seismic imaging challenges associated with the trap(s) formed early on in the process of inversion. Also, migration may become tortuous due to the structural complexity or the source rock units may be uplifted above the hydrocarbon generation window effectively terminating the charge once the inversion occurred.

For any particular structure the evidence for inversion is typically provided by subsurface data sets such as reflection seismic and well data. However, in many cases the deeper segments of the structure are either poorly imaged by the seismic data and/or have not been penetrated by exploration wells. In these cases the interpretation of any given structure in terms of inversion has to rely on the regional understanding of the basin evolution with evidence for an early phase of substantial crustal extension by normal faulting. In some cases, where the regional geology has not been properly appreciated, the simple reactivation of pre-existing structures related to earlier episodes of shortening in the area was erroneously classified as inversion.

There might be a negative bias towards the prospectivity of inverted structures using examples from exhumed margins. Another bias may stem from the typical assumption that the generating kitchen tends to be in the syn-rift sequence of the inverted structure. Highly successful exploration cases in basins which have not experienced severe uplift and exhumation, like the giant gas discoveries in the deepwater Levant Basin, highlighted the importance of source rocks not being constrained to the syn-rift basin fill but rather located in the post-rift regional sequence, but in a pre-inversion stratigraphic position.

Data availability

Some of the seismic lines used in this study are confidential and not available publicly.

Author contribution

Gabor Tari wrote the text and compiled the manuscript, Didier Arbouille analysed the IHS Markit global data base, Zsolt Schleder provided structural geology expertise and Tamás Toth provided 3D reflection seismic and well data from SW Hungary.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We are pleased to thank Jonas Kley and Piotr Krzywiec for inviting this paper to the special issue of Solid Earth and for their editorial efforts. We are grateful to IHS Markit for the access to their extensive worldwide exploration and production data base in order to find reported cases of inverted traps. Discussions about inversion tectonics with Albert Bally, Bill Bosworth, Frank Horváth and Hans-Gert Linzer are also acknowledged. Peter Pernegr kindly drafted some of the figures. This paper is dedicated to the memory of Prof. Albert W. Bally (1925-2019) who was the PhD Advisor of the first author at Rice University, Houston, Texas.

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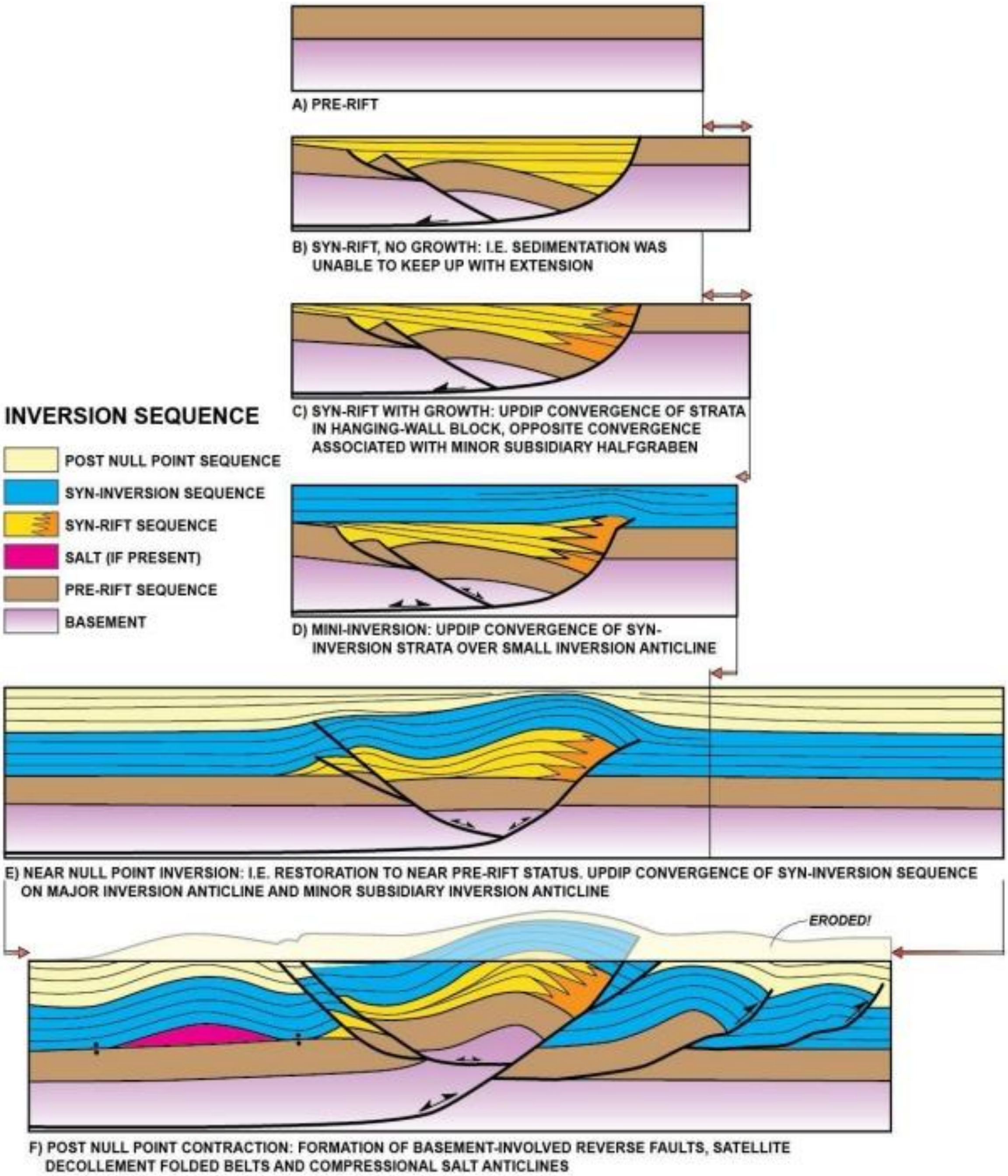

Figure 1: Extended version of Bally's (1984) original inversion model. This cartoon was redrafted after an unpublished figure made by Albert W. Bally in the early 2000s at Rice University to show the progression of inversion tectonics into the formation of an incipient folded belt. Specifically, he made this cartoon with the western high Atlas of Morocco in mind (e.g. Hafid et al., 2006) that is why salt is shown here as a detachment level accommodating some of the contraction.

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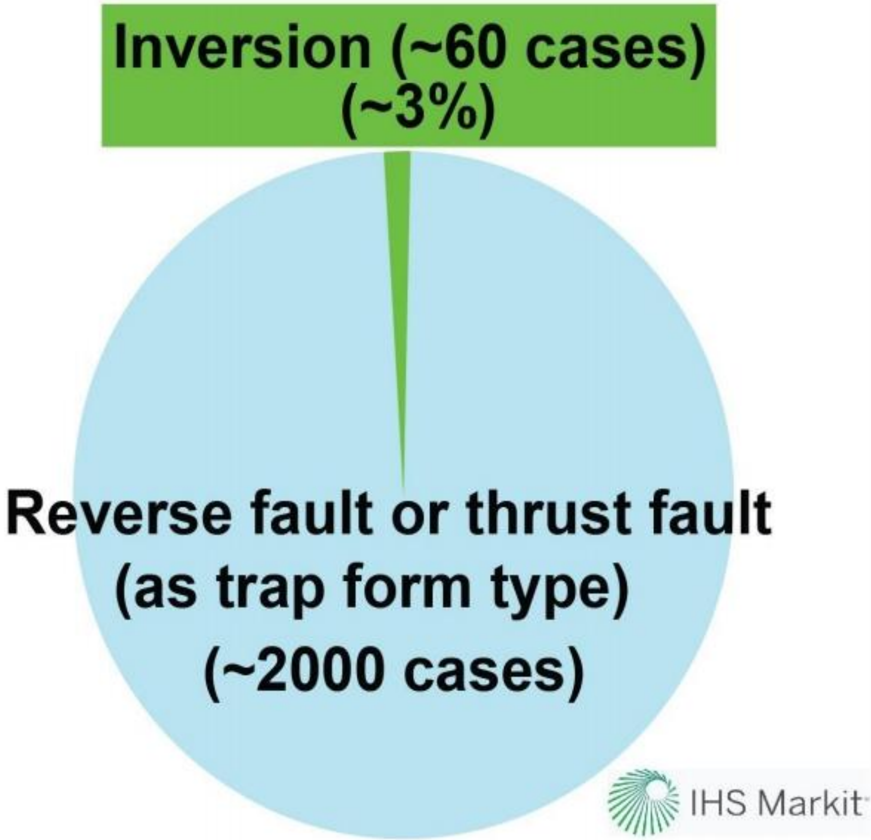

Figure 2: Outcome of a worldwide (excluding onshore US and Canada) data base search using hydrocarbon fields and discoveries with circa 2,000 reservoir units. In these reservoir units the "trap form" type was classified as “reverse fault” or “thrust fault”. Interestingly, within these 2,000 cases we have found only about 60 matches for inversion as a "trap forming mechanism". This translates to only about 3%, a strikingly low proportion. We believe that inversion tectonics may be unrecognized in many fields globally and therefore it remains underreported. Courtesy of IHS Markit.

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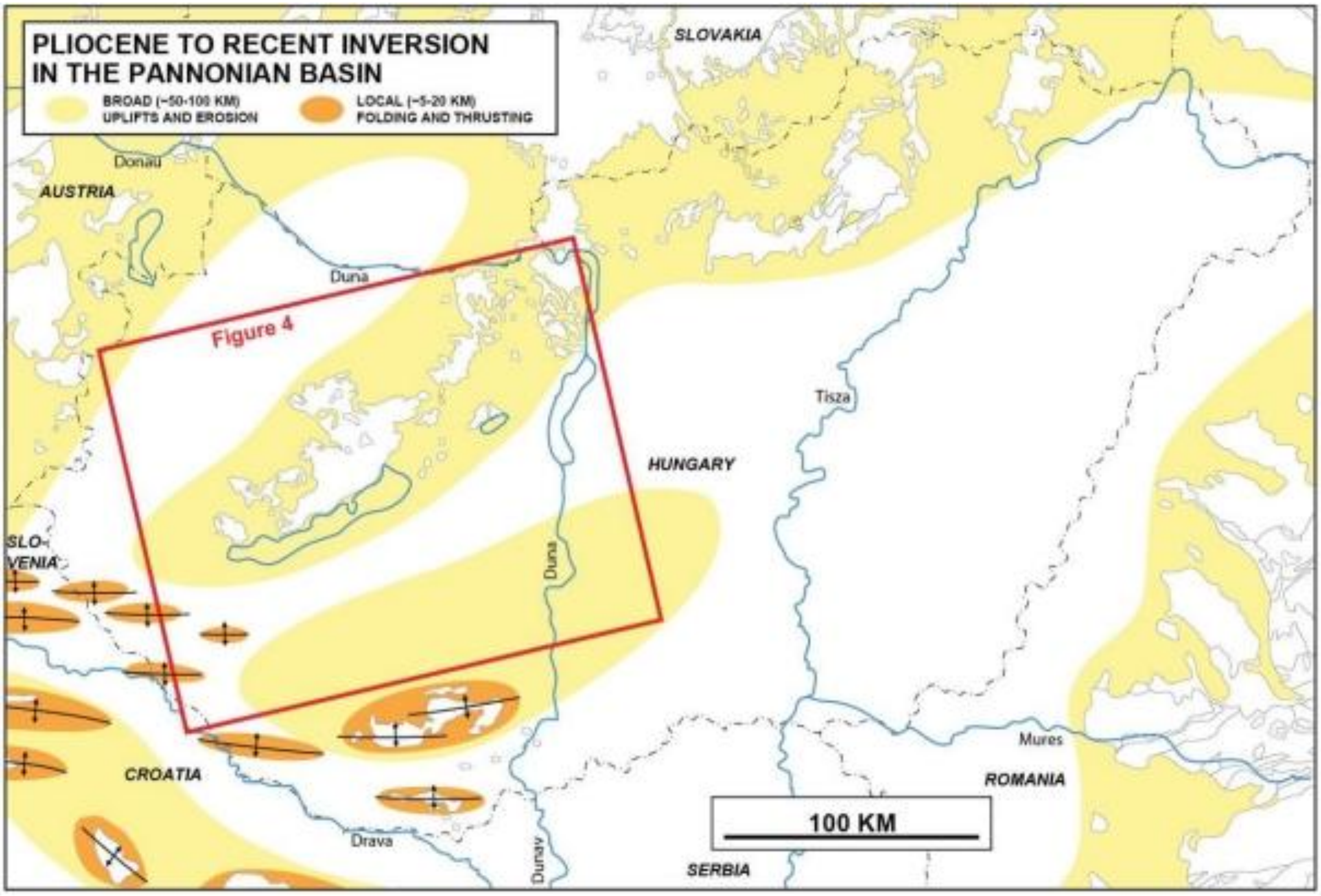

Figure 3: Regional map of the central part of the Pannonian Basin adapted from Tari (1994) who distinguished for the first time two classes of inversion tectonics in this basin. These two end-member categories of uplift are attributed them to regional-scale and local-scale structural inversion tectonics. Especially, the map-view pattern of the smaller-scale inverted structures suggests that inversion and uplift are propagating into the intra-Carpathian region from the W.

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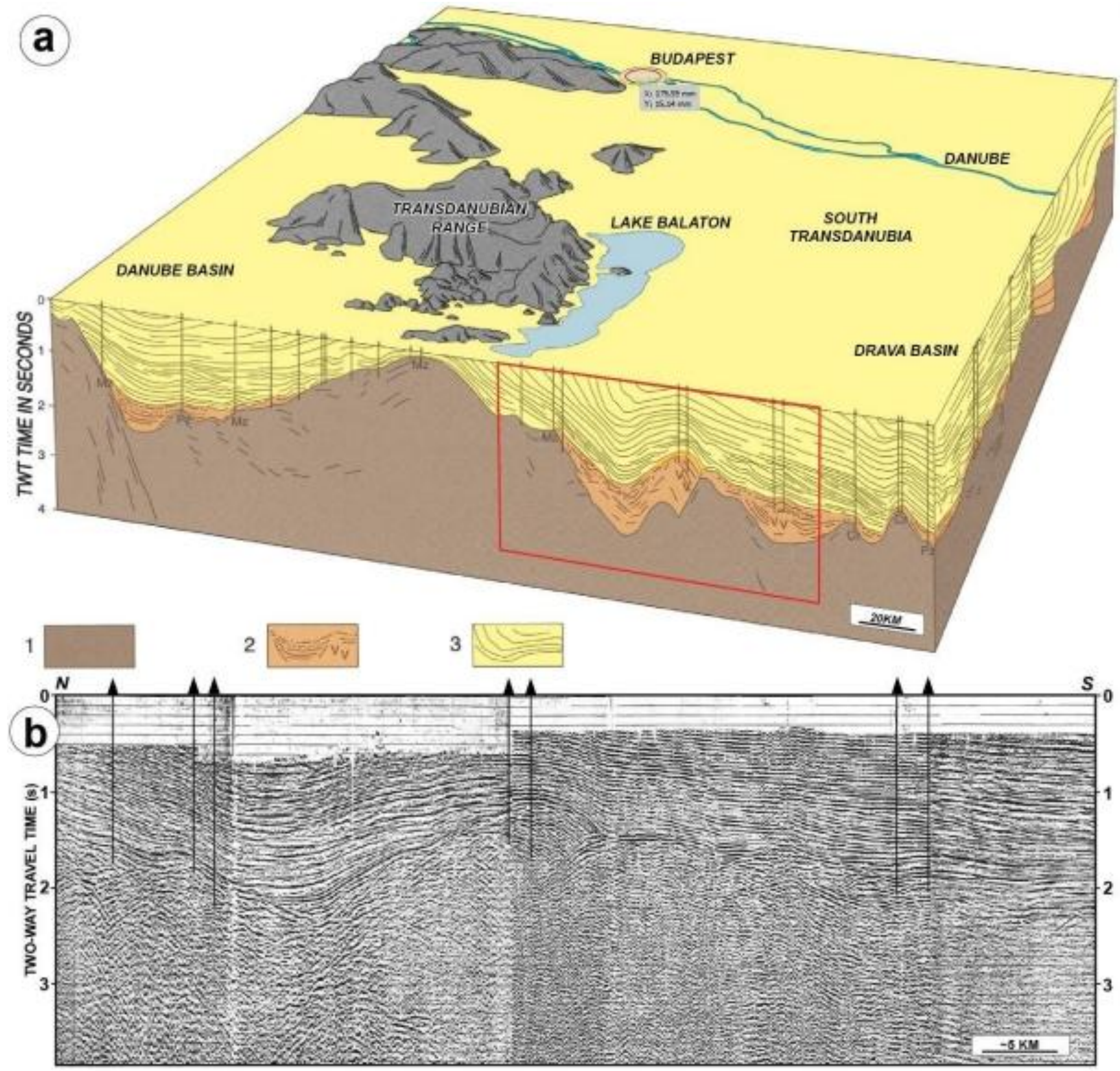

Figure 4: a) Block diagram of the Transdanubian part of the Pannonian Basin to illustrate the structural and stratigraphic conditions, and their relation to surface morphology. The regional- scale upwarping of pre-Cenozoic rocks of the Transdanubian Range north of the Lake Balaton (for location, see Fig. 3) is the consequence of Pliocene to Recent basin inversion (adapted from Horvath and Tari, 1999). Legend: 1, Mesozoic-Paleozoic bedrocks; 2, mid-Miocene syn- rift strata; 3, late Miocene to Pliocene post-rift strata b) Vintage 2D seismic section (Tari, 1994; Rumpler and Horváth, 1988) as part of the regional seismic line shown above as a line drawing. The core of the young anticline in the center was drilled by wells Vése-1 and -2 and penetrated thick syn-rift Miocene strata. The overall geometry of the structure suggests that a syn-rift half-graben was inverted, just like in the case of the Budafa anticline (Fig. 5).

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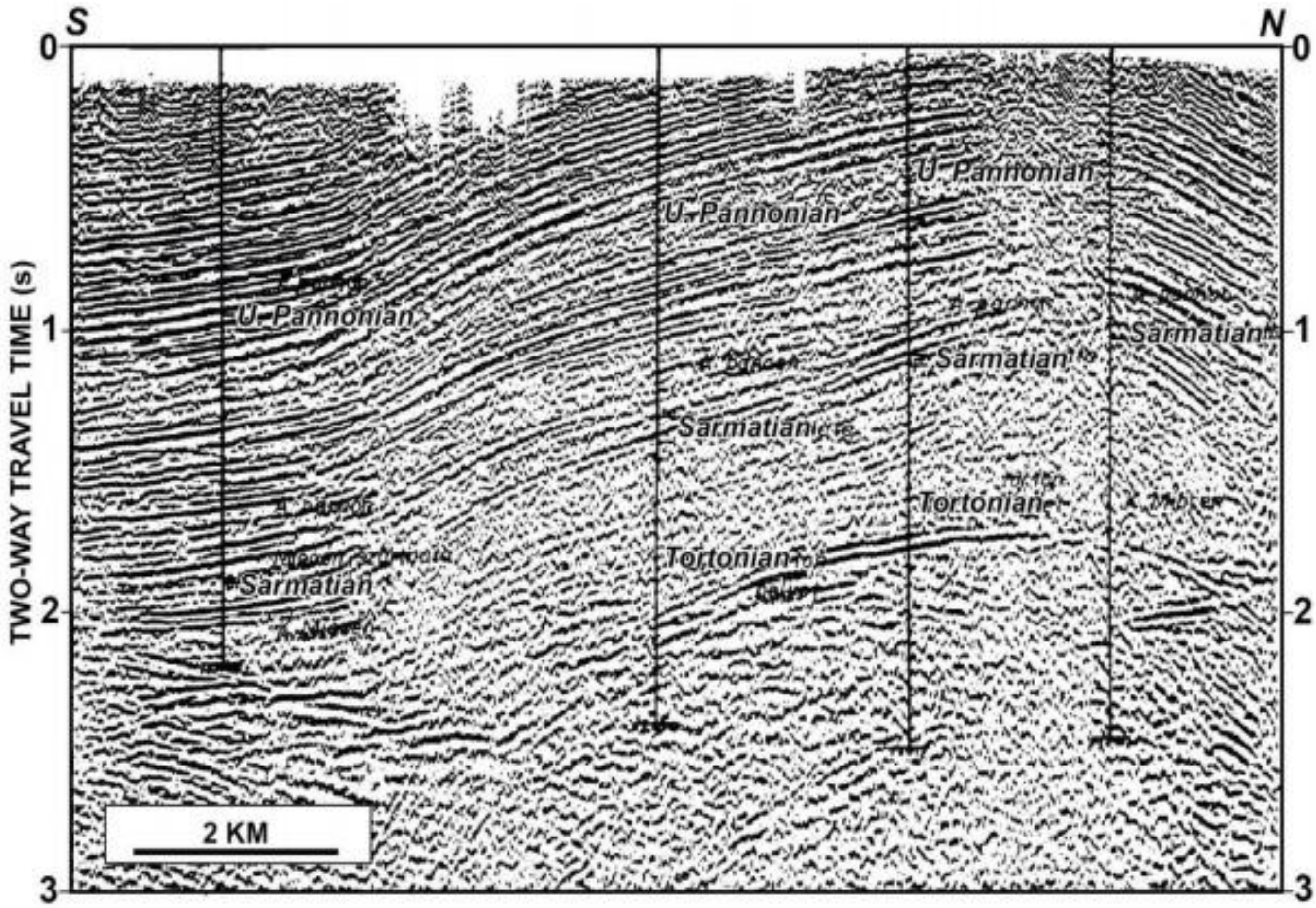

Figure 5: Vintage 2D reflection seismic illustration of the Budafa field (Dank, 1988; Pogacsas et al., 1994). The asymmetric nature of the surface anticline suggests an underlying master fault on the northern flank of the structure. Even on this moderate to poor quality vintage line one can interpret the thickening of the Upper-Middle Miocene ("Sarmatian-Tortonian-Helvetian") strata beneath the apex of the anticline . This provides evidence for the latest Pliocene to Quaternary inversion of a pre-existing Miocene syn-rift half-graben. Unfortunately, the seismic data quality is not good enough to properly delineate the position of the master fault, let alone that of the null-point.

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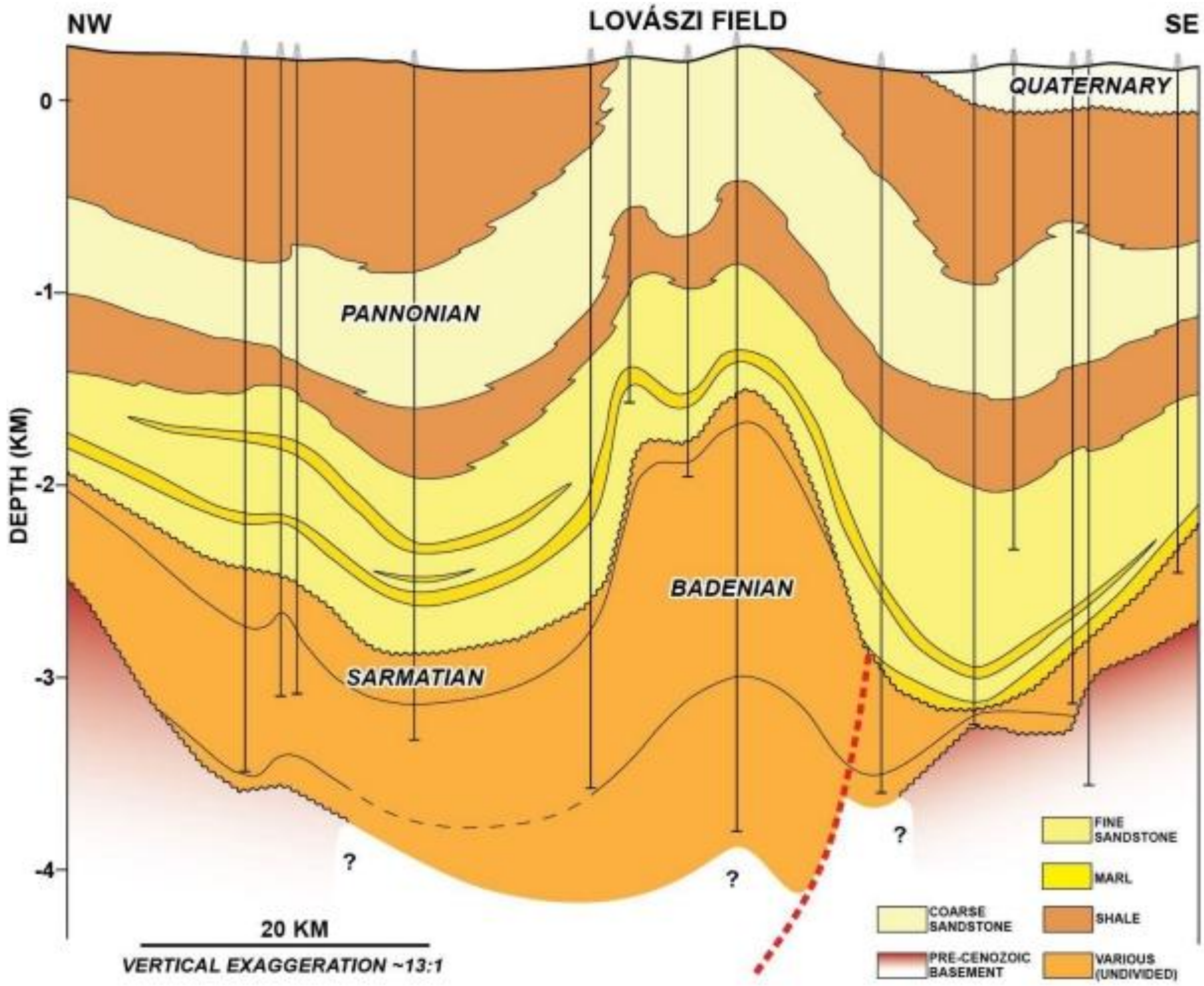

Figure 6: This sub-regional lithostratigraphic transect, crossing the Lovászi field, was redrafted after Juhász (1994, 1998). Her study was not devoted to the structural evolution of the area but rather to the correlation of various lithologies of the Miocene and
545 **Pliocene sequence using primarily well data. Note the missing Pannonian sequence above the Lovászi anticline which could have a 800-1000 m thickness. Given the slightly asymmetric shape of the Lovászi anticline we inferred the presence of a master syn-rift fault and added it to the original illustration (dashed red line) beneath its southern flank (cf. Figure 7).**

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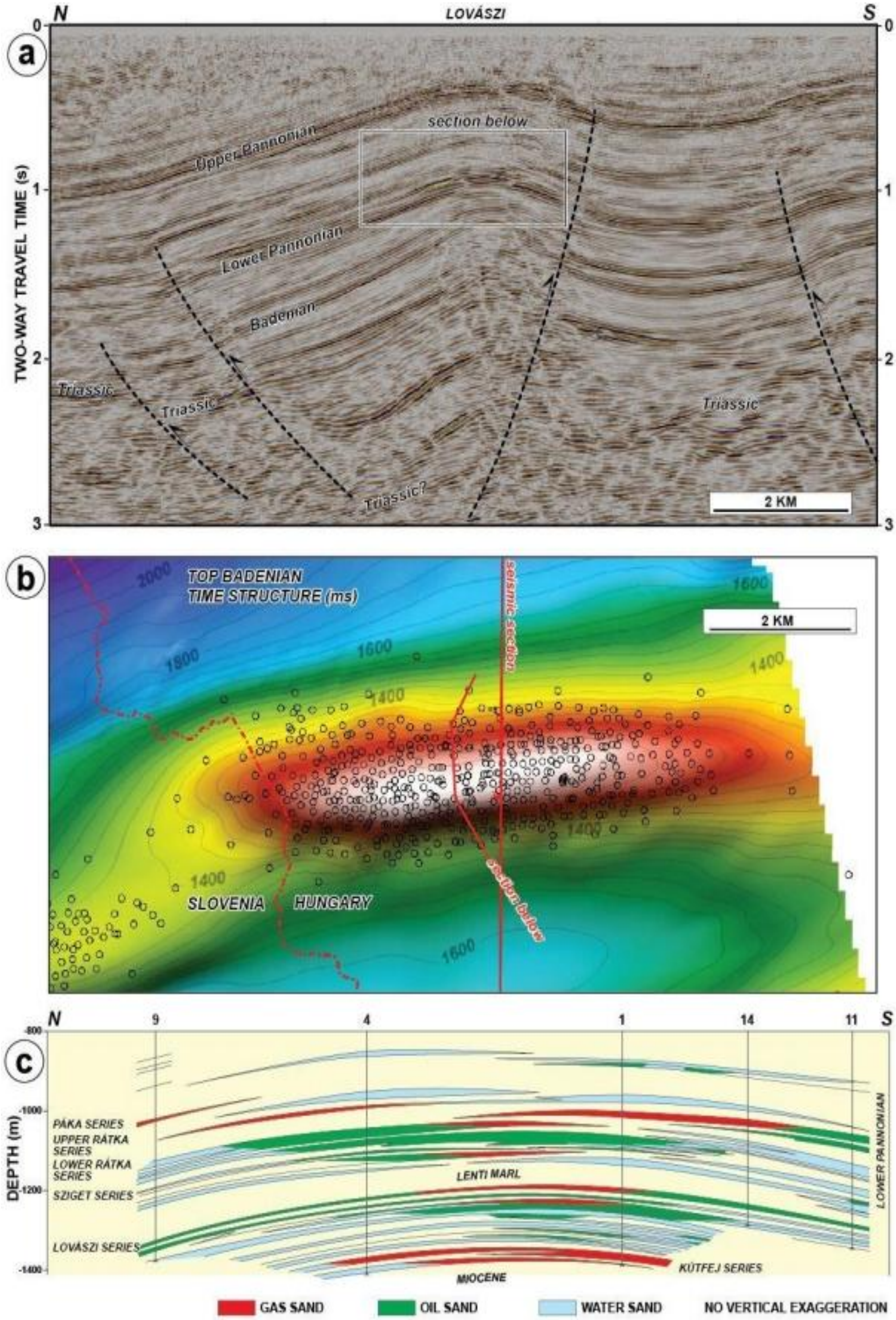

550 **Figure 7. Highlights of the Lovászi field, at the border of Hungary and Slovenia, for location see Figure 3. a) 3D reflection seismic example across the field adapted from Tóth and Tari (2015); b) two-way travel time structural map on a top Badenian (Middle Miocene) seismic horizon with a 25 ms contour interval and c) well-based cross section across the field based on Dank (1985).**

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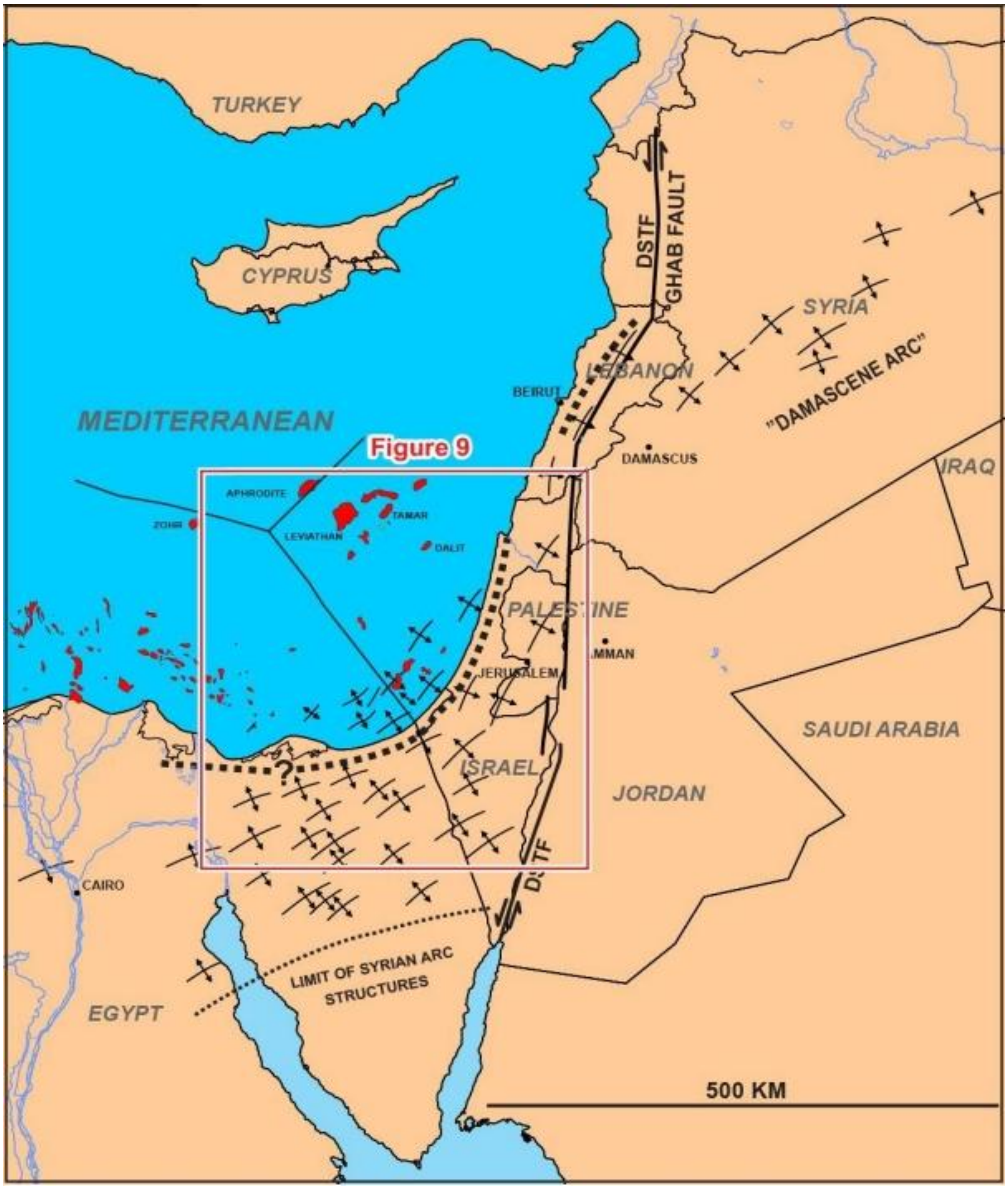

Figure 8: Regional map of the Syrian Arc anticlines (sensu Krenkel, 1925) in the Eastern Mediterranean compiled mostly after Walley (1998). Note that the Damascene segment of the Syrian Arc corresponds to the Palmyride detachment folded belt and therefore it cannot be considered *sensu stricto* as an inverted region.

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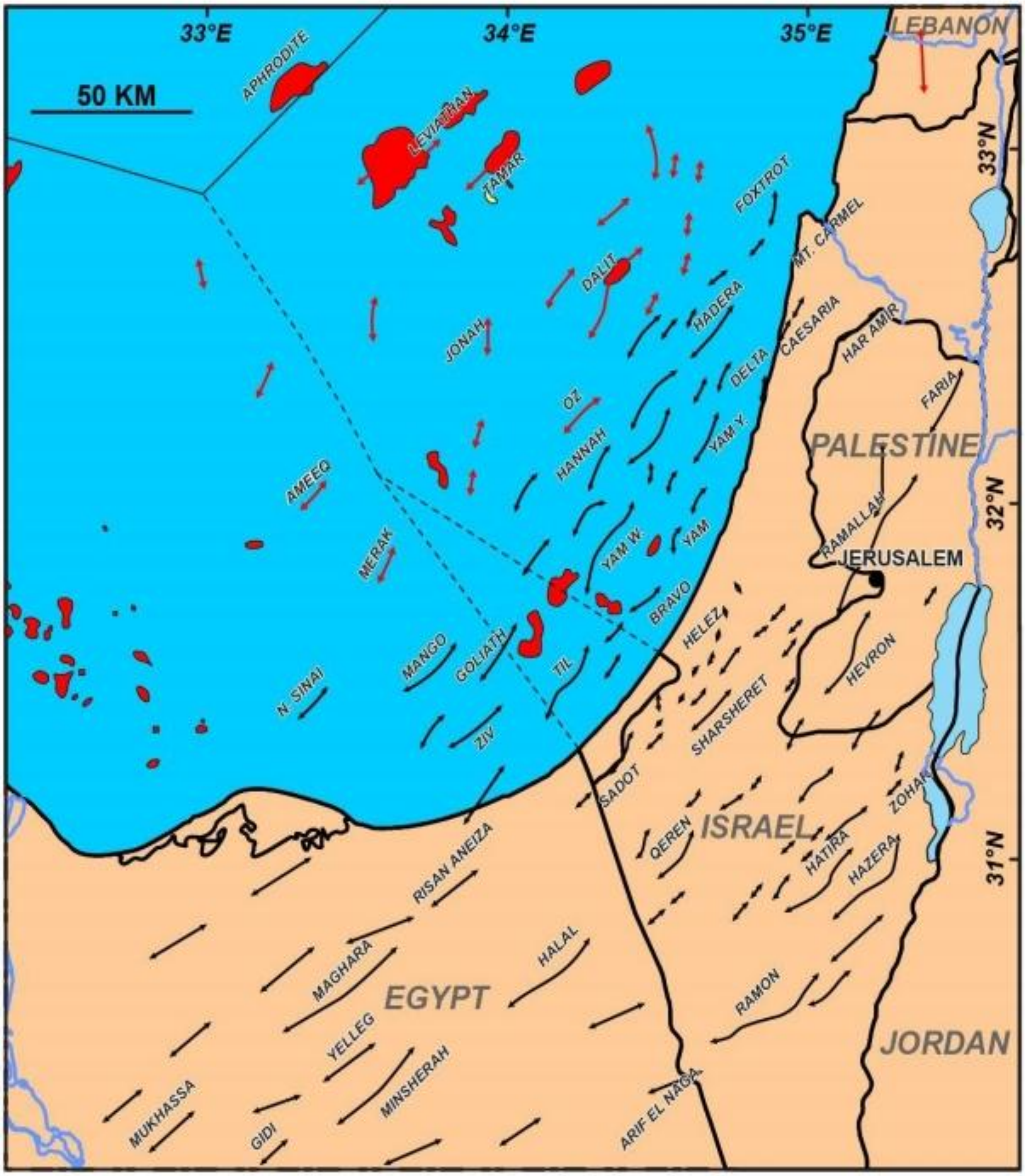

Figure 9. Close-up of the Syrian Arc anticlines, in the border region between Egypt and Israel, modified from Gardosh and Tannenbaum (2014) with some additions in the Egyptian offshore. For location see Figure 8. The anticlinal axes in black
560 **correspond to the early Syrian Arc deformation (Late Cretaceous), whereas the red ones formed during the late Syrian Arc inversion (Late Cenozoic). Note the location of the Mango and Tamar anticlines in Egypt and Israek, respectively.**

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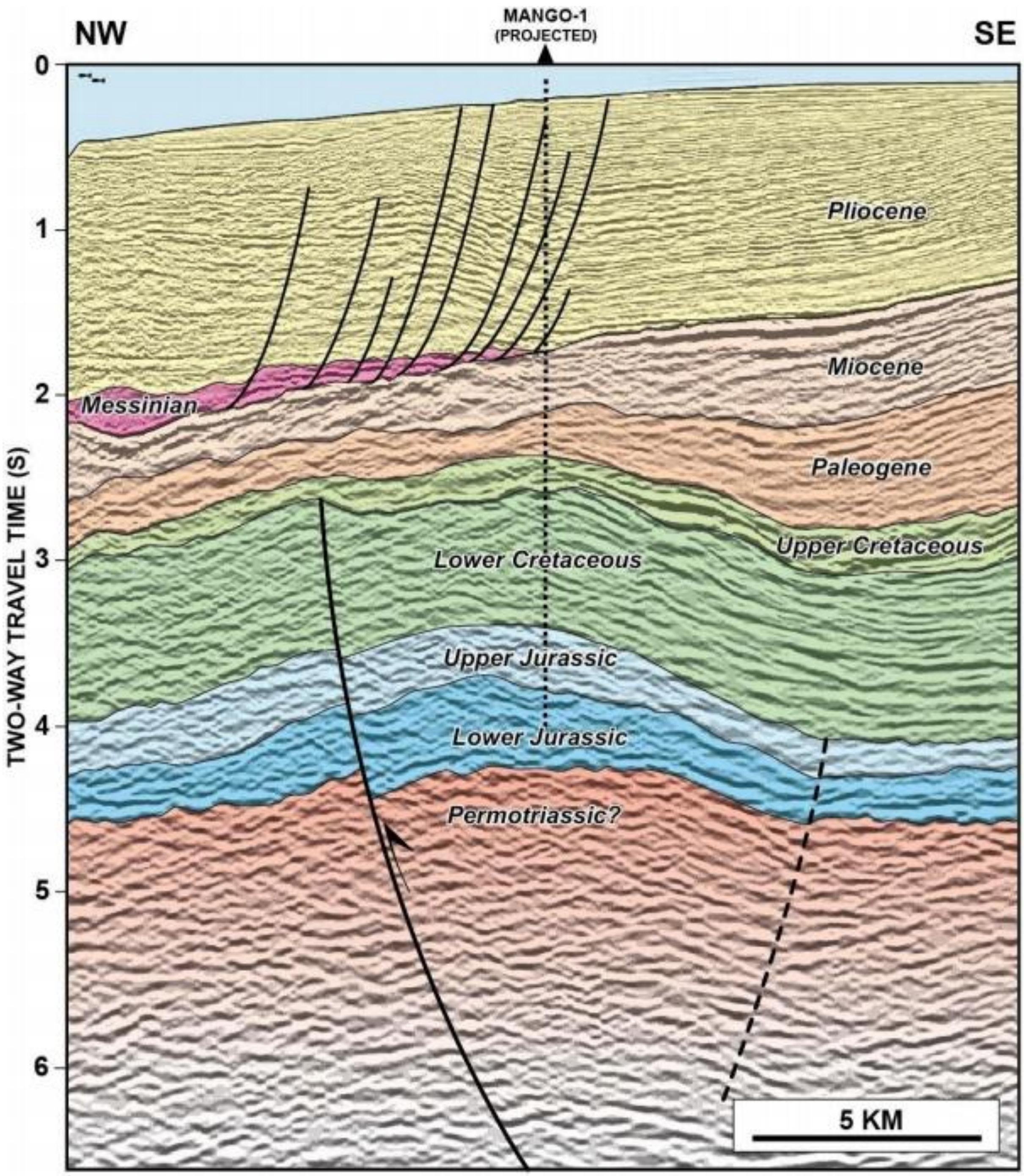

Figure 10. 2D reflection seismic profile across the Mango oil discovery in offshore Sinai, Egypt (see location in Fig. 9). The large syn-rift master fault controlled the deposition of the Lower Jurassic to Lower Cretaceous sequence. The subsequent Late Cretaceous Syrian Arc inversion is responsible for the formation of the asymmetrical anticline (modified after Yousef et al., 2010).

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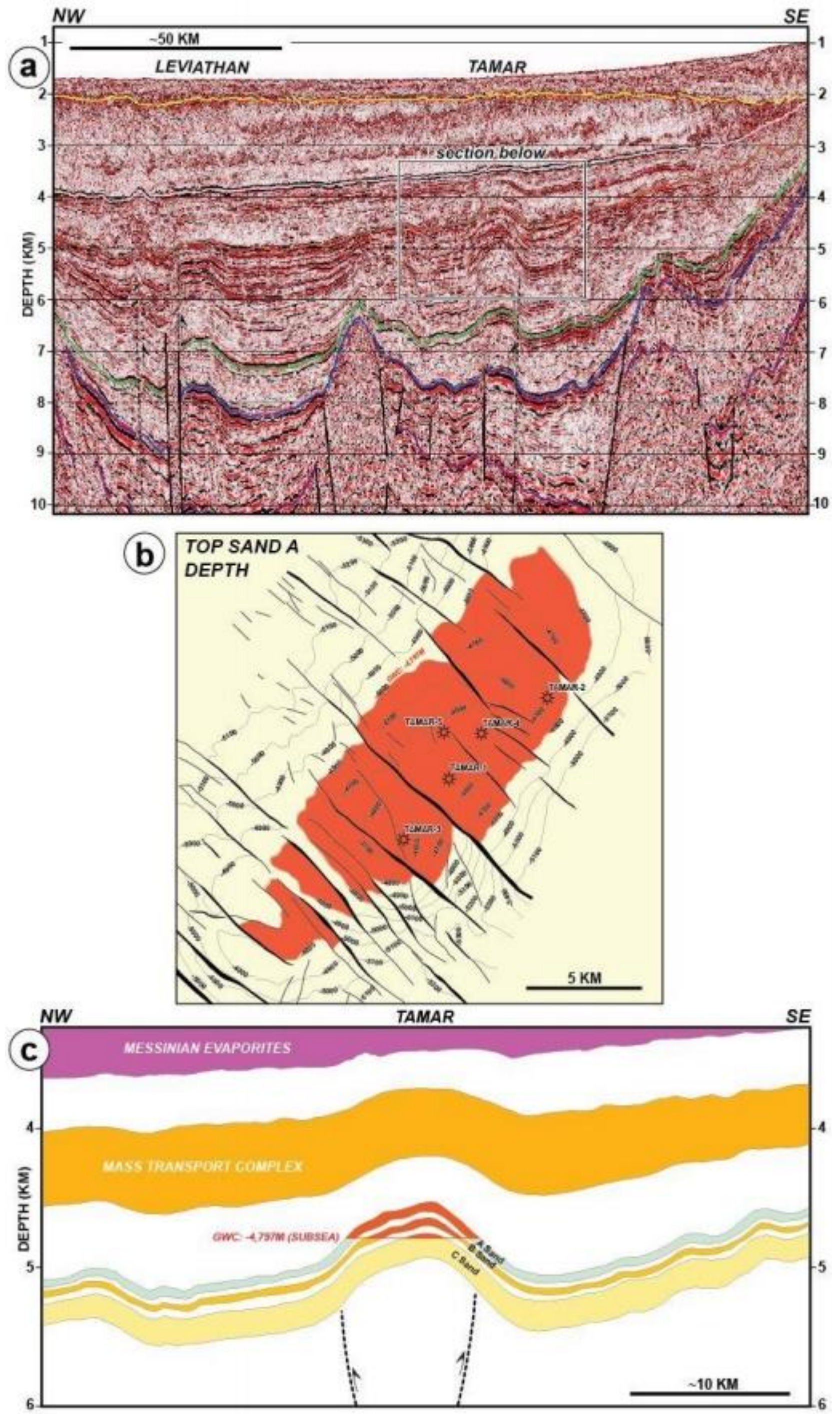

570 **Figure 11: Highlights of the Tamar field, offshore Israel, for location see Figure 10. a) Regional-scale PSDM seismic reflection section across the Tamar gas field, offshore Israel, (courtesy of Spectrum), b) structural depth map on the Sand A reservoir level (Needham et al., 2017) and c) simplified cross section across the field based on Needham et al. (2017).**

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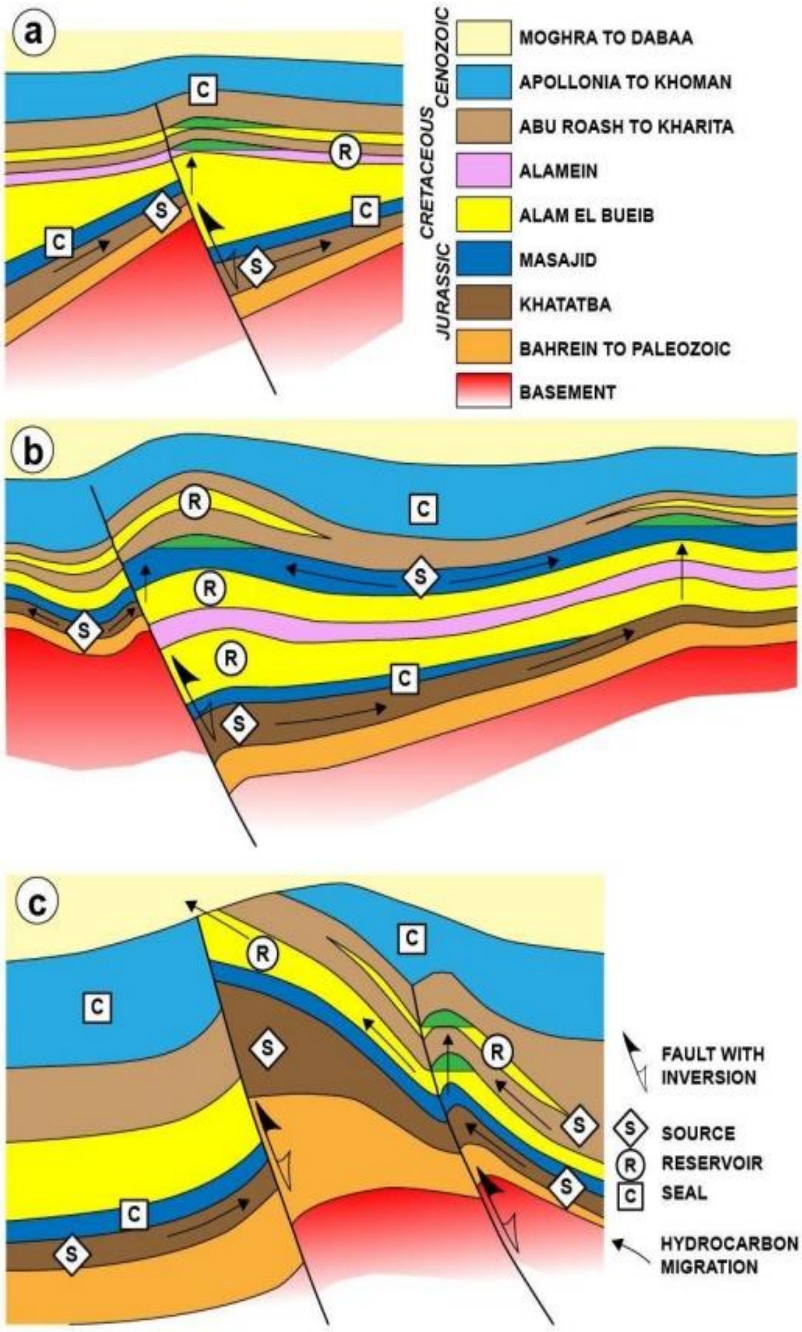

Figure 12: Cartoons of potential charge scenarios of structures associated with inversion structures, redrawn from Bevan and Moustafa (2012). These examples from the Western Desert of Egypt illustrate well the increasing severity of inversion with the corresponding variations on the petroleum system migration patterns. The three progressive stages are shown using the oil field examples of (a) Razzak, (b) Mubarak and (c) Kattaniya. See text for a generalization of the impact of inversion tectonics on petroleum systems and exploration efforts.

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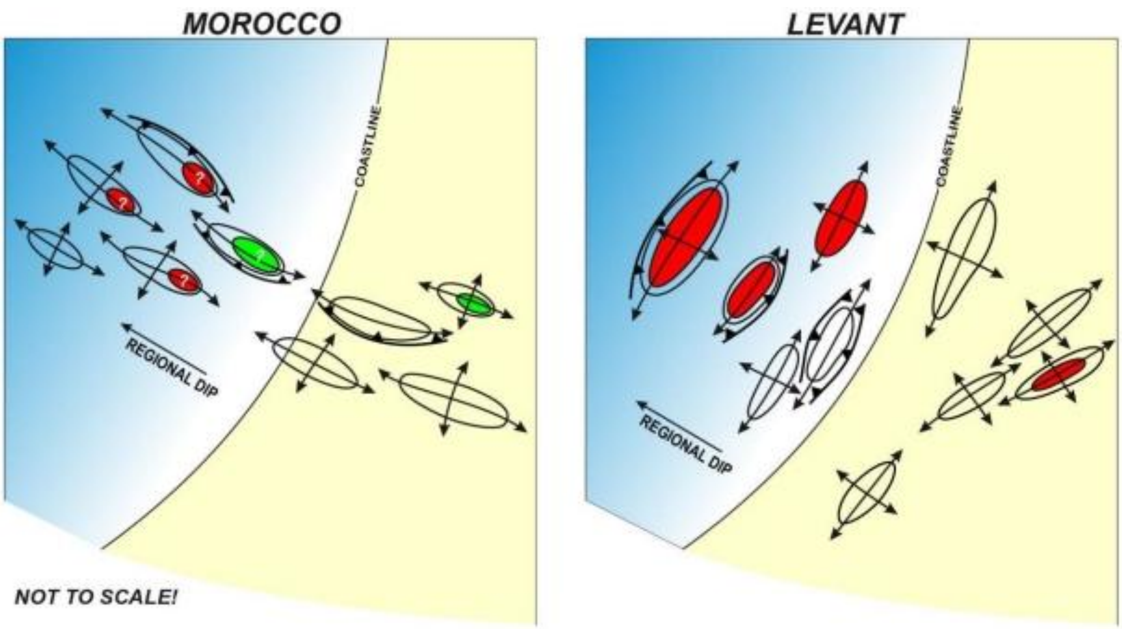

Figure 13: The impact of the trend of inverted structures versus the regional dip, adapted from (Tari and Jabour, 2011). Large gas
580 **discoveries of the last decade in the deepwater Levant Basin are all associated with inverted structures which strike parallel with the margin (Fig. 9). In Atlantic offshore Morocco, there are no deepwater discoveries yet (note the question marks!), but many prominent inverted anticlines exist both offshore and onshore (e.g. Hafid et al., 2006; Tari and Jabour, 2013). From a trapping point of view, if inverted structures strike perpendicular to the regional dip in a basin then it translates to an optimum situation as to the size of the four-way closures of the anticlines. In contrast, in a basin where the inversional anticlines have the same trend as**
585 **the regional dip, the four-way closures on the updip end of the structures tend to be much smaller.**

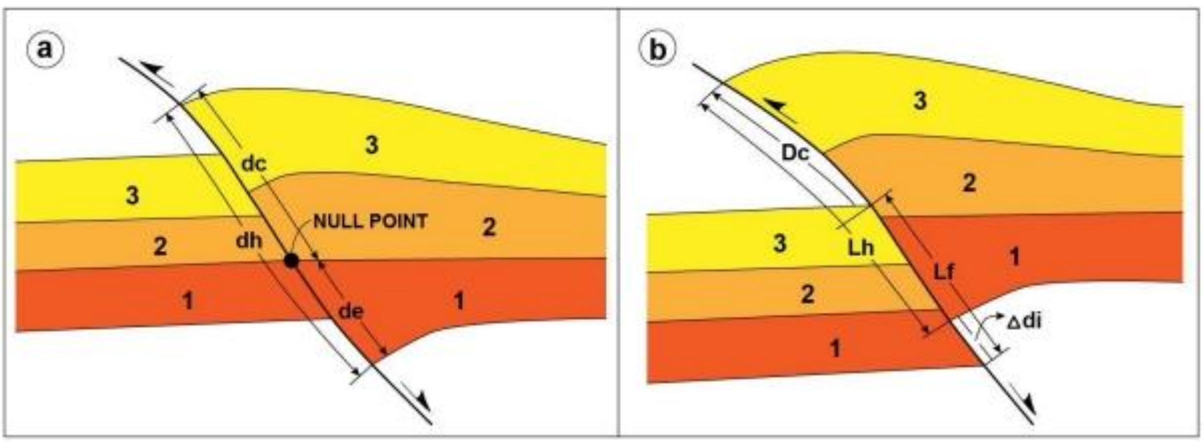

Figure 14: Two methods to determine the inversion rate in a quantitative manner by a) Williams *et al*. (1989) and b) Song (1997). In our view, the quantification of inversion tectonics remains a challenge as the deeper section beneath an inverted anticline is
590 **typically not well imaged seismically and/or not drilled due to the greater depth.**