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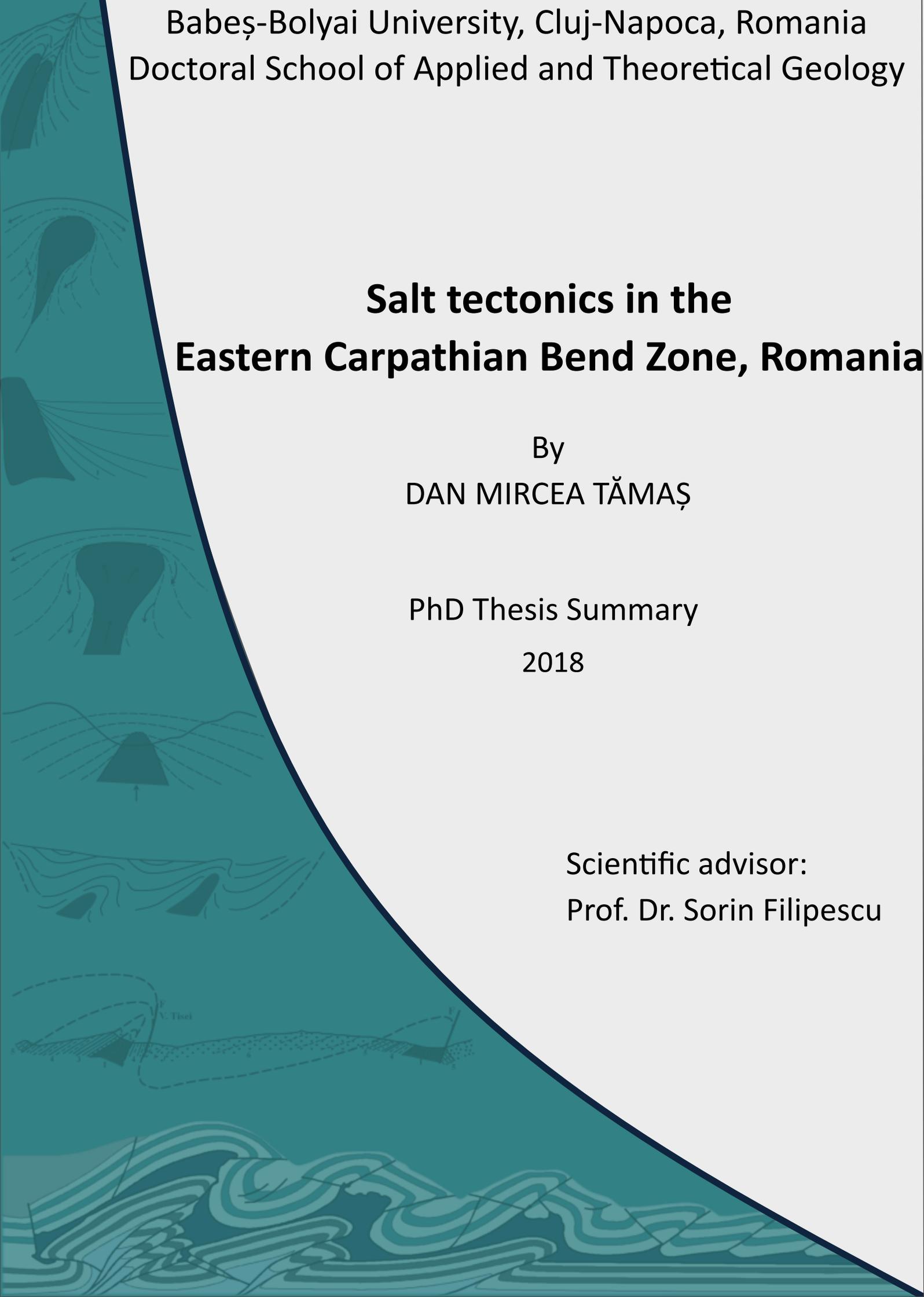Doctoral School of Applied and Theoretical Geology

Salt tectonics in the
Eastern Carpathian Bend Zone, Romania

By
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PhD Thesis Summary

2018

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Key words: salt tectonics, diapirism, analogue modelling, structural geology, fold and thrust belts, hydrocarbons, Eastern Carpathian Bend Zone, Diapir Fold Zone.

Chapter 1 - Introduction

The first chapter of the thesis presents the rationale behind the research topic of the thesis, the area of interest, objectives, thesis outline and how the results were disseminated during the studies. Part of the work performed during the PhD study has contributed to a number of publications. Some of this information has been included in the thesis to a smaller or greater extent.

The topic of the thesis, salt tectonics, is of worldwide importance to geological research and petroleum geology as it is often one of the key features related to major hydrocarbon provinces. Understanding salt tectonics in these hydrocarbon provinces has preoccupied geoscientists for more than 160 years, and it is the same case for the Romanian Eastern Carpathian Bend Zone (CBZ).

The area hosts many of the most significant onshore oil fields in Romania, the one associated to the main diapir lineament (Gura Ocniței – Moreni – Florești – Băicoi – Țintea). One of the major complications in interpreting the diapir evolution in this area is the relatively poor quality of the seismic data (in the proximity of the diapir and subsalt) and also the relatively old well data.

Since the availability of 3D seismic data in the area of interest, there were little to no attempts to understand the timing and evolution of diapirism in this area and also how salt tectonics affected sediment distribution and the related fault network. This study is the first to use scaled analogue modelling in the attempt to explain the structural evolution of the diapirs in the Diapir Fold Zone (to our current knowledge).

The primary objective of this research is to gain a better regional and sub-regional understanding regarding salt tectonics in the CBZ. To fulfil the objectives, several questions have to be answered:

- How the modern-day understanding of the diapirs in the DFZ came to be?
- What were the historical models regarding the kinematic evolution of these diapirs?
- What were the main factors controlling the structural style?
- Can we understand more about the effects of basal decollement efficiency and salt thickness on the kinematic evolution of the diapirs in the DFZ?

- What is the geometry of the sub-salt structures? Can we use analogue modelling to predict this?
- Is the traditionally used stratigraphy (mostly in the hydrocarbon industry) still correct?
- Can we have a better time correlation of some events (i.e. the base Maeotian unconformity)?
- How did these diapirs evolve and what was the trigger and timing of their rise?
- What is the 3D geometry (size and shape) of these diapirs? Can these be mapped in more detail?
- Is it possible to understand more regarding the post-Sarmatian tectonic events in the area with the available data?
- Did diapirs and diapirism have any effect on reservoir distribution and compartmentalisation?

Chapter 2 - Evaporites, salt tectonic and diapirism

Evaporites are many times present in sedimentary basins as it is also the case in our area of interest, the Romanian Eastern Carpathian Bend Zone. Chapter 2 is meant to present a short introduction to the topic of evaporites and especially salt. The chapter deals with the physical and mechanical properties of salt, salt tectonics, and their importance for the hydrocarbon industry.

Evaporites are defined as being a salt rock that was initially precipitated from a saturated surface or near surface brine in hydrologies driven by solar evaporation (Warren, 2016). It is essential that water outflow by evaporation to exceed the water inflow in the restrictive basins where evaporites are deposited (Hudec & Jackson, 2007).

When referring to the term "salt", one may refer to all rock bodies that are primarily composed of a crystalline aggregate of the mineral halite (NaCl). Most of the salt structures/bodies contain various amounts of other evaporites like anhydrite and gypsum, or non-evaporites (Hudec & Jackson, 2007).

Polycrystalline halite rock is composed of 0.01 mm to dm halite grains containing impurities, secondary minerals or fluid inclusions (Urai et al., 2008). Rock salt is relatively incompressible and has a density, $\rho_s = 2200$ kg/m^3, and viscosity that ranges between $10^{17} - 10^{19}$ Pa s (Jackson & Talbot, 1986; Weijermars et al., 1993; Hudec & Jackson, 2007).
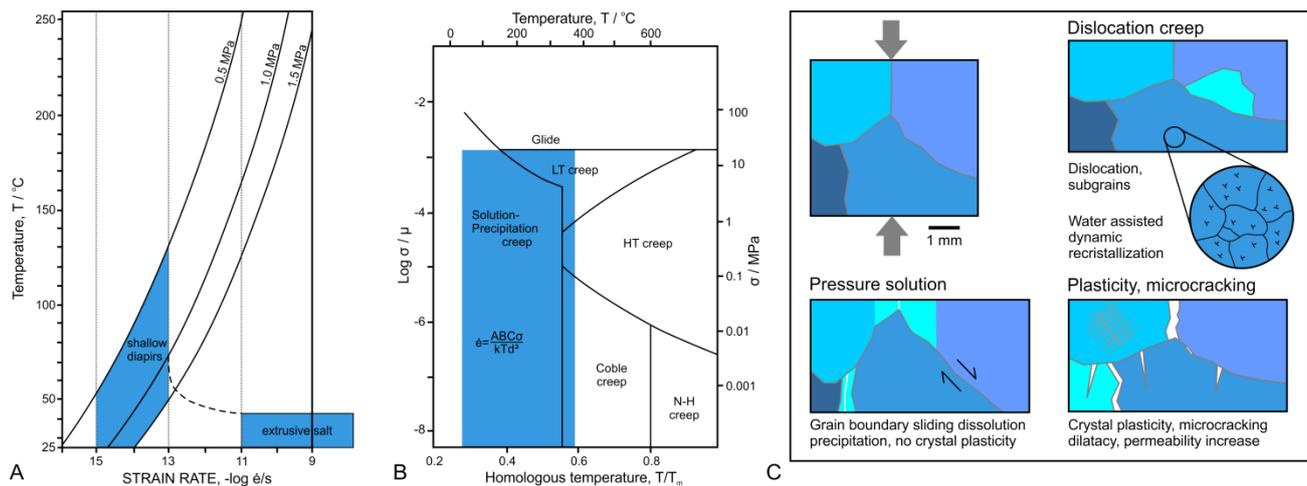
Figure 1. Salt flow conditions and deformation mechanisms. A- power law behaviour of dry rocksalt, where the relation between the steady-state strain rate (e) and differential stress is non-linear (after Jackson & Talbot, 1986); B- deformation mechanism map for damp rock salt with a grain size of 1mm. blue shade represents the conditions for natural salt flow. LT-low temperature; HT-high temperature; N-H- Nabarro Herring (after Urai et al., 1986); C- scheme of microstructural processes that can take place during rock salt deformation at temperatures between 20-200°C. Different color shades represent different cristal orientations (after Urai et al., 2008).

The mechanical properties of salt are different from most of the clastic and carbonate rocks, as it deforms as a viscous or power-law fluid under low strain rates (geological conditions) (Urai et al., 1986; Jackson & Talbot, 1986). One of these differences in comparison to the brittle rocks is the strength of salt, which is a lot weaker both in tensional and compressional strength than the surrounding rocks (Jackson & Vendeville, 1994). The deformation mechanisms for dry and wet salt are different as the former deforms by dislocation creep and the latter by diffusion creep (solution-precipitation creed) mechanisms (Urai et al., 1986, 2008; fig. 1A, B, C).

The position and shape of the salt bodies depend on how the brittle overburden deforms and that the dominant force that drives salt tectonics is differential loading. This differential loading can be of three types: gravitational, (fig. 2a, b, c), displacement (fig. 2d, e) or thermal loading (Hudec & Jackson, 2007). In gravitational loading, you either need a load variation (i.e. sedimentation, deformation or erosion) that creates a pressure gradient (fig 2a) or a tilt in the layers that create an elevation head gradient (fig. 2b) or a combination of the two, in order to start salt flow. In the cases where there is no differential load or tilt, there are no pressure head or elevation head gradients. Thus the salt will not flow (fig. 2c), even if the base of the salt layer is uneven (Hudec & Jackson, 2007; Jackson & Hudec, 2017).
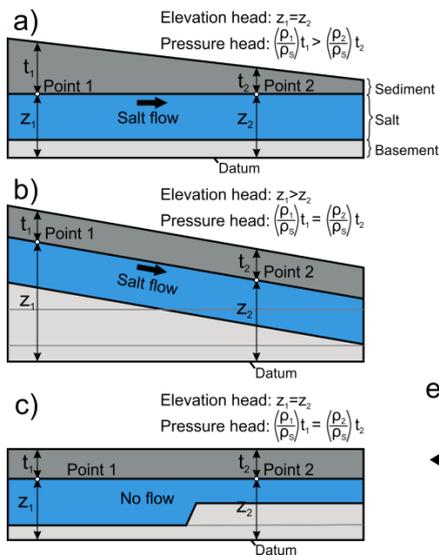
Figure 2. Schemes of hydraulic head gradient (a, b, c) and displacement loading (d, e) as driving forces in salt tectonics. a- lateral barying overburden thickness above a horizontal salt layer with constant thickness; b- constant overburden thickness above an inclined salt layer with constant thickness; c- constant overburden thickness above a flat top salt layer with varying thickness; d- horizontal salt load during shortening; e- horizontal salt unload during extension; (after Hudec & Jackson, 2007).

While the salt is flowing, it can exhibit a combination of channel flow (Poiseuille flow) and shear flow (Couette flow). The Poiseuille has the highest flow rate in the centre of the salt sequence, as the layers confining the evaporite sequence decrease the flow rate due to boundary drag effects. The Couette flow occurs in a salt system where the confining layers have a relative translation one to the other, which leads to a simple shearing of the salt layer. In most of the salt layers subjected to compression or extension, the flow exhibited by salt is a combination between the Poiseuille and Couette flows. Salt drag along a detachment level can lead to produce thicker salt in the down-dip area of the slide, than the original thickness (Davison et al., 1996; Hudec & Jackson, 2007; Warren, 2016; Jackson & Hudec, 2017).

One of the main reasons for the large interest in salt tectonics is the relationship between it and hydrocarbons. Salt tectonics has implications not only in the trapping (fig. 3) but also in the maturation and migration of hydrocarbons. In most of the cases, salt structures create perfect
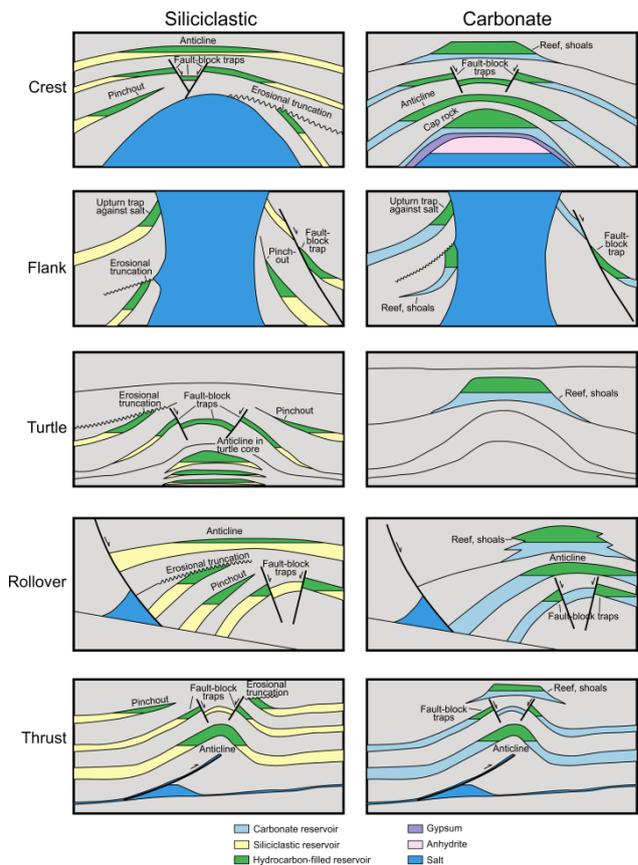
Figure 3. Examples of salt-related traps, classified into five settings. Each of these settings creates a structural high, but through a different process (after Jackson & Hudec, 2017).

seals, but the leaking potential of salt welds is highly important in understanding the hydrocarbon system in an area affected by salt tectonics. Hydrocarbon reservoirs are also affected by salt tectonics, not only in the sense of folding, faulting, and fracturing but also by how it affects reservoir distribution and diagenesis (Jackson & Hudec, 2017).

Chapter 3 - Overview of the Romanian Eastern Carpathian Bend Zone

Chapter 3 is presenting an overview on the Romanian Carpathians and their foreland basin, creating the regional context for the area of interest, the DFZ. This chapter will present the structural evolution of the Carpathians, the development of the Carpathian Foreland Basin and the stratigraphic framework of the area. As this study focuses on the late Eocene to Pleistocene stratigraphic record, in the DFZ (fig. 4), which was deposited in relation to the paleogeographic and tectonic evolution of the area, only the stratigraphy of interest was described in the thesis. Also, this chapter presents the stratigraphy as published in the literature, or seen in well or outcrop data, without any age reinterpretation (see Chapter 7 for discussions regarding the uncertainties related to the stratigraphy).

The Romanian Carpathians are a highly arcuate Alpine orogen (fig. 4), recording the evolution of the Alpine Tethys between the latest Jurassic to mid-Miocene (Săndulescu, 1984, 1988; Csontos & Varos, 2004; Schmid et al., 2008). The first collisional event started in the late Jurassic and emplaced nappe structures of the inner Romanian Carpathians during the mid-Cretaceous (Săndulescu, 1984; Csontos & Varos, 2004). [Note, in this thesis, we follow the timescale of the Eastern Paratethys (e.g. Laskarev, 1924; Cicha et al., 1998) developed for the Dacian Basin (e.g. Jipa & Olariu, 2009).]

The thin-skinned deformation of the Carpathians has been translated above the Moesian Platform (lower plate). The Mesozoic deformations of the Carpathians are characterised by strong basement involved thrusting (e.g. Dacia, East Vardar, Ceahlău-Severin; fig. 4). These basement nappes crop out in the western part of the Eastern Carpathians (Bucovinian nappes), the South Carpathians (Getic nappes), and form the basement of the Transylvania Basin (Băncilă, 1958; Săndulescu, 1984, 1988; Maţenco & Bertotti, 2000; Krézsek & Bally, 2006; Maţenco, 2017).
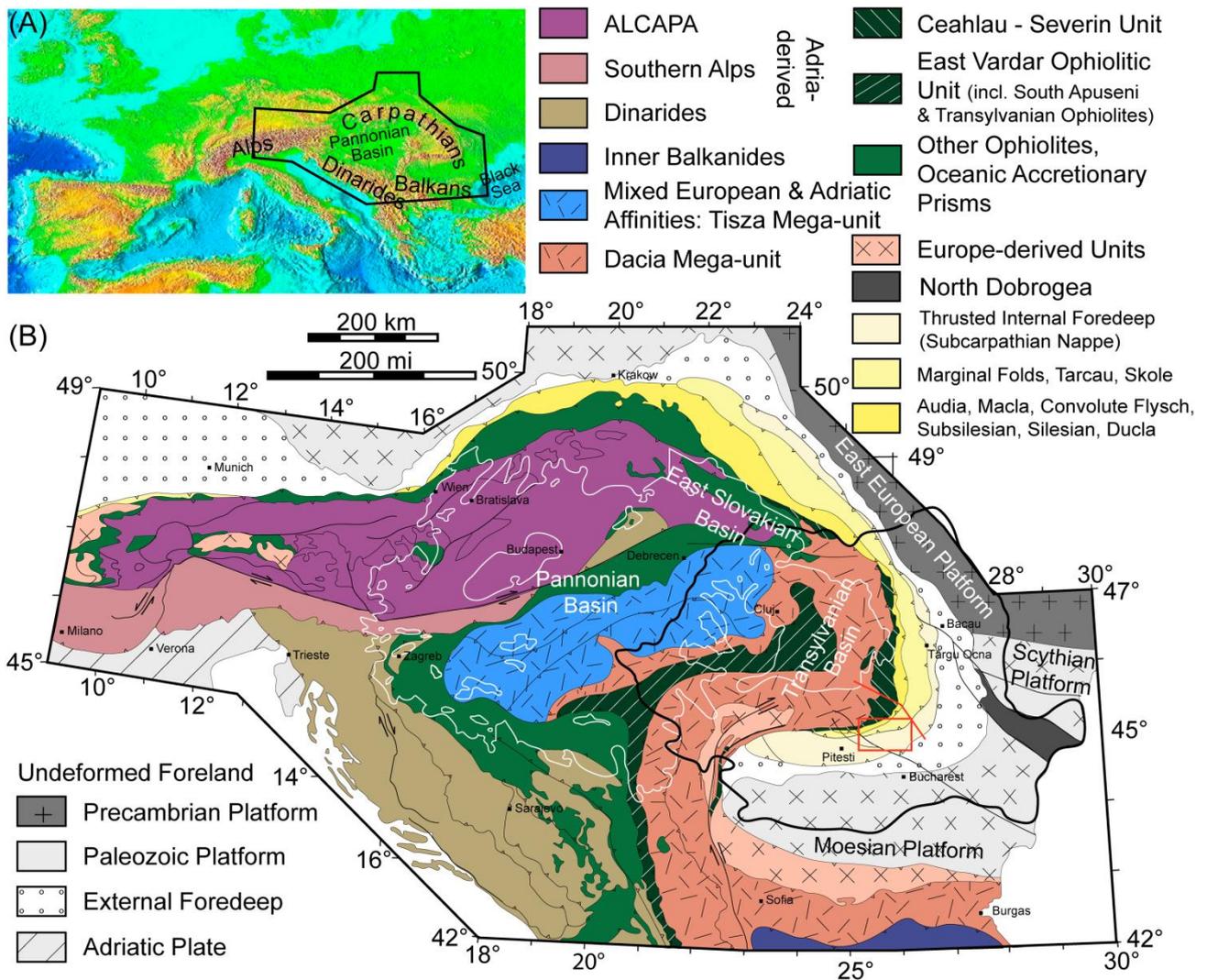
Figure 1. *Regional geological setting of the Romanian Carpathians (Schmid et al., 2008; Merten et al., 2010; Tămaş et al,. 2018a). (A) The topography of the Alpine – Dinaride – Carpathian system with solid black polygon indicating the location of Figure 1B (after Merten et al., 2010). (B) Simplified tectonic map of the Alps, Carpathians, and Dinarides.*

Starting with the Burdigalian (lower Miocene), the subduction of the Carpathian embayment created a forward-breaking sequence of nappes (convolute flysch, Macla and Audia nappes). Following the latest Burdigalian to Badenian (middle Miocene) thrusting of the Tarcău Nappe, the Sarmatian (middle Miocene) paroxysm of subduction emplaced the Subcarpathian Nappe over the undeformed foreland (Băncilă, 1958; Săndulescu, 1984, 1988; Maţenco & Bertotti, 2000; Merten et al., 2010; Maţenco, 2017). Maţenco and Bertotti (2000) described a strike-slip regime during the latest Sarmatian to early Maeotian, resulting in the occurrence of ~NW-SE dextral strike-slip faults in the CBZ.

One of the particularities of the Carpathians is the presence of two different salt horizons: the "lower salt" (early Burdigalian) and the "upper salt" (middle Badenian) (i.e. Murgoci, 1905; Popescu

et al., 1973). These evaporites have been originally deposited in the foreland area of the Carpathians and later have been incorporated in the nappe structure of the Carpathians. While the Burdigalian salt is restricted to the Carpathians foreland basin, the Badenian salt also extends into the back-arc area of the Carpathians (e.g. Transylvanian Basin, East Slovakian Basin) (e.g. Popescu et al., 1973; Babel, 2004; Krézsek & Bally 2006; de Leeuw et al., 2010). In regional profiles presented by Ștefănescu (1986), three major detachment horizons have been described. The lowermost is within the Cretaceous, followed by the lower Burdigalian salt and the third being the Badenian. It is along this Badenian salt decollement that the whole fold and thrust belt is translated onto the Moesian lower plate.

The most recent deformation of the Carpathians (the Wallachian phase) is late Miocene (Maeotian) to Recent in age (Hippolyte & Săndulescu, 1996). This was not related to the subduction process but to the intra-plate compression accommodated by thick-skinned deformation (Cloetingh et al. 2004), which resulted in up to 4 km of uplift (until Recent), erosion and out of sequence thrusting (Sanders et al., 1999; Merten et al., 2010). During this phase, many pre-existing thrusts were reactivated and produced several out-of-sequence thrusts (Maţenco, 2017).

The post-Oligocene shortening in the Eastern Carpathians was estimated at 130 km, most of it (108 km) during the mid-Miocene (Badenian-Sarmatian) and the rest (22 km) afterwards (Roure et al., 1993).

Chapter 4 - Understanding salt in orogenic settings: the evolution of ideas in the Romanian Carpathians

The CBZ is an area of worldwide importance for the history of salt tectonics and represents the type area for the term diapir. Chapter 4 aims to present, in detail, the original ideas regarding salt tectonics in the Romanian Carpathians and to describe the historical development of these concepts. A particular focus of this chapter will mainly be on the work of the outstanding Romanian geologist, Ludovic Mrazec, who defined the "folds with piercing core" and coined the term "diapir".

Salt tectonics is a general term representing lateral and vertical salt flow, trans-stratal salt movement, salt pillowing and diapirism (e.g. Hudec & Jackson, 2007; Warren, 2016). The concepts related to salt tectonics have evolved gradually for the last 150 years, and several conceptual breakthroughs in understanding the mechanism of salt tectonics have taken place (Jackson, 1995,

1997). In a retrospective paper on salt tectonics, Jackson (1995) separated the evolution of thought into three eras: pioneering (1856 - 1933), fluid (1933 - ~1989) and brittle (~1989 - Present). During "pioneering era", there was a search for a general hypothesis for salt diapirism. This was the time when the discordant character of the salt has been observed (e.g. Posepny, 1871) and Mrazec (1910) formulated his views on the diapirism. In the "fluid era", most researchers postulated that gravity can generate diapir growth due to buoyancy effects, i.e. the density contrast between the salt and overburden. It was eventually realized that buoyancy could not be the primary control on diapirism (Vendeville & Jackson, 1992a, b). This gave rise to the "brittle era", and it was acknowledged that external (tectonic) forces are needed to generate space for the diapir to rise. This latter paradigm governs understanding of salt tectonics since the late 20th century.

The diapirism concept proposed by Mrazec (1910) has had a long-lasting influence on the subsequent salt tectonics interpretations worldwide. Although general historical reviews of salt tectonics often acknowledge this (O'Brien, 1968; Jackson, 1995), the details of his ideas are poorly documented (e.g. Mrazec, 1905, 1907, 1926). This paper aims to summarise the history of Mrazec's ideas developed in the "Diapir Fold Zone" (DFZ) of the Romanian Carpathians (fig. 4). While describing the historical salt ideas, we tried to avoid the use of modern salt terminology (e.g. "salt weld" or "passive diapirism") in order to keep the meaning and attitude of the text to resemble that of the original papers. Some more recent interpretations for the Diapir Fold Zone were also included, in order to illustrate the present day understanding of the salt tectonics (Ștefănescu et al., 2000; Schléder et al., 2014, 2016a, b). Evolution of concepts regarding salt tectonics

In Romania, discussions regarding salt tectonics started with the notable observations of Posepny (1871) who demonstrated the discordant and extrusive nature of the mid-Miocene salt in the Transylvanian Basin (fig. 5). The cross-section (fig. 5) that Posepny (1871) made to illustrate the Praid diapir shows features both of the salt deformation within the diapir and the deformation of strata adjacent to the diapir (i.e. rim synclines, upturned flaps). He also interpreted the salt domes in Transylvania (e.g. Krézsek & Bally, 2006) to
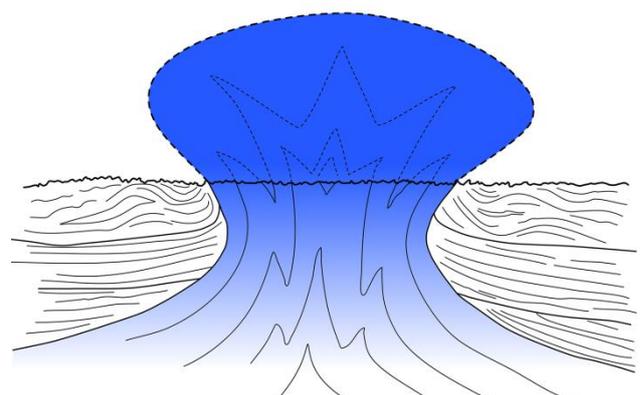
Figure 5. Cross section through the Praid diapir is indicating the discordance between the layers flanking the diapir and the salt dome itself. The dashed part of the figure has been eroded. (Posepny, 1871; Tămaș et al., 2018a). [Note: the scale has deliberately been omitted as in the original drawing. The diapir is about 3 km (1.9 mi) tall.]

have intruded or pierced their overburden due to a tectonic disturbance in the strata in which they are emplaced.

In January 1907, Mrazec gave a talk at the Romanian Science Society about the "folds with piercing core". The minutes of this meeting appeared in the "The Bulletin of the Society of Sciences" (in Romanian) (Mrazec, 1907) and have frequently been, and erroneously, cited as the paper in which the term "diapir" was introduced. The minutes of the meeting do not contain the term diapir. The term "diapir" is first found in a talk entitled "On the formation of the Romanian petroleum deposits", which Mrazec gave at the 3rd International Petroleum Congress held in Bucharest, in September 1907 (Mrazec, 1910). In this talk, he referred to the "folds with piercing core" as "diapir folds". The original publication is in German and hence the term appeared as "Diapiren Falten" although the word "diapir" originates from the Greek word "διαπείρειν" (to pierce). The conference paper appeared three years later in print and thus is the correct reference to the first mention of "diapir" (Mrazec, 1910).

The 3rd International Petroleum Congress was organised in Bucharest, Romania, to acknowledge the importance of the Romanian oil industry. The conference was run in a remarkably similar fashion to the modern ones (organised sessions according to topics) and attracted many geologists, mining engineers, and international oil reporters (890 registered congress members) (Owen, 1975). At this conference, Mrazec introduced the term diapir in one of his talks (Mrazec, 1910; fig. 6). Mrazec's talk had a long-lasting impact on the prestigious audience (oil company directors and officials), and salt specialists quickly adopted his ideas in Europe (Owen, 1975). In particular, his idea of orogenic forces controlling the diapirism was appreciated (Mrazec & Teisseyre, 1902; Mrazec, 1905, 1907, 1910, 1926). These ideas competed with those of Posepny (1871) suggesting the importance of molecular forces within the salt or the hypothesis of Arrhenius and Lachmann (1912, 2002), that postulated the rise of salt caused by the pressure of the roof rock given its higher specific gravity. This theory was later rejected (Mrazec, 1926).

The first internally coherent salt tectonic concept in Romania was put forward by Posepny (1871). He described discordant salt structures in the Transylvanian Basin and illustrated details for the internal deformation of the salt diapirs and structures in the surrounding sediments. Many of his insights are still valid today (ductile salt, rim-synclines, and upturned flaps).

In the late 19th century the significant hydrocarbon discoveries in the Diapir Fold Zone shifted the focus to this area and prompted several academics to work on salt tectonics problems.
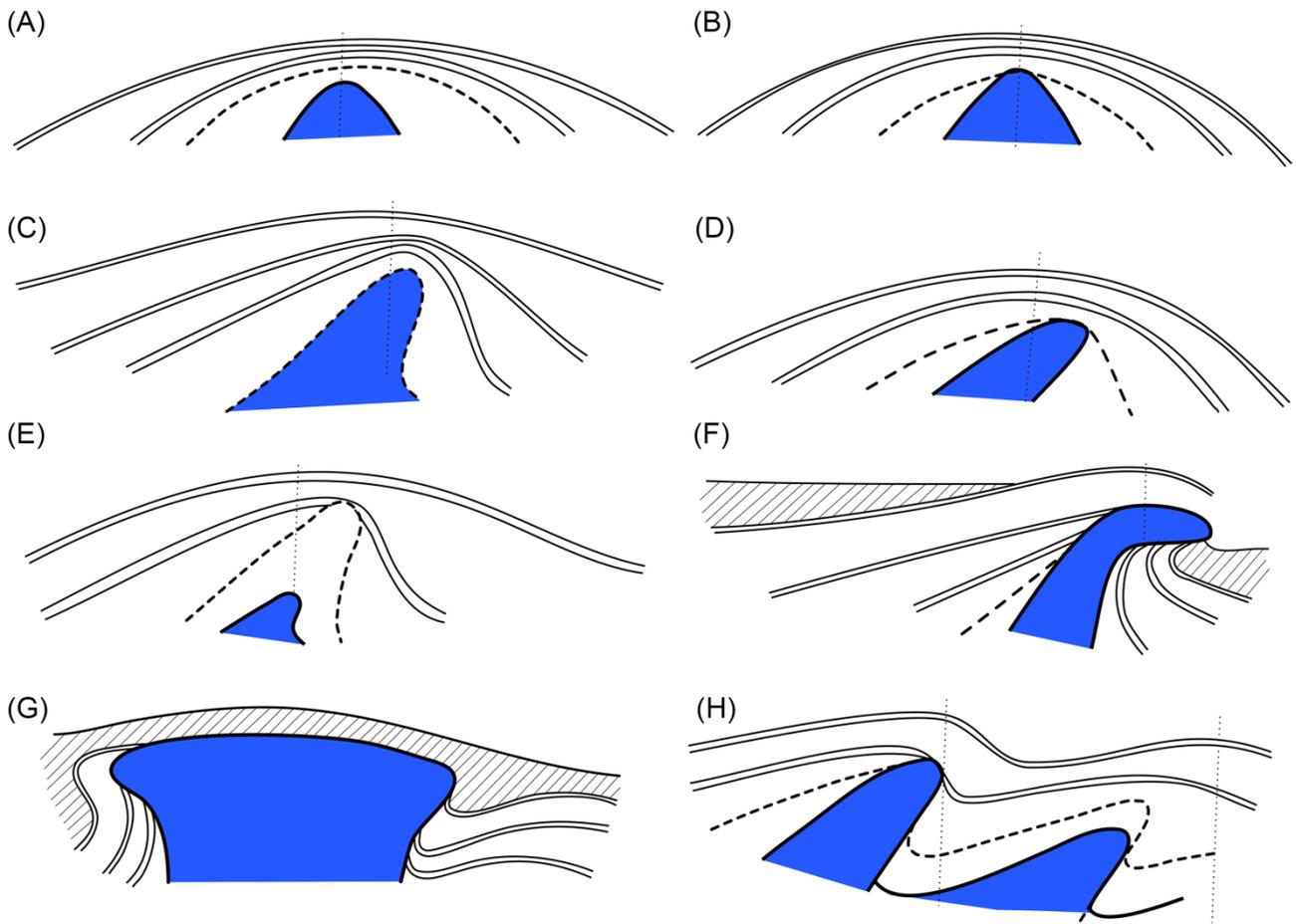
Figure 6. *Sketch of types of diapirs present in worldwide petroleum areas, as presented by Mrazec in 1907, when he introduced the term diapir. Mrazec (1910) described the diapirs by how much the core pierces the roof strata and where the dotted line (the axis of the fold as he called it) coincides or falls away from the crest of the diapir. (A) and (B) describe normal diapir folds, whose apex coincides with the crest of the diapir, (C) the diapir is slightly tilted with the fold axis falling away from the crest of the diapir, (D) the diapir is sharply compressed, isoclinal and tilted (he gave as example Filipeștii de Pădure), (E) the fold axis lies laterally from the diapir crest, (F) this type of diapir fold is tilted and thrusted. The pierced layers are folded and thinned adjacent to the diapir (he gave as example the Gura Ocniței – Moreni and Țintea – Băicoi diapirs), (G) schematic longitudinal section trough of the Băicoi (left) and Țintea (right) areas, with the crest of the diapir swelling over the sides, (H) series of diapirs that present a step-like decrease in piercing amplitude. On the surface, the overlying strata are gently folded, and the synclines are asymmetrical. The fold axis falls (in this example) on the side of the diapir, in the synclines. Mrazec described this step-like decrease of the diapirs to be characteristic for the Diapir Fold Zone (i.e. Colibași - Moreni) (Mrazec, 1910; Tămaș et al., 2018a). [Note: as the original drawings do not contain a scale, the present figure has been redrawn as the original.]*

Most of the diapirs in the Diapir Fold Zone were observed piercing the crest of the anticlines. Ludovic Mrazec considered these "folds with piercing core" or "diapir folds" to be the product of compressional forces combined with the pressure exerted by the rocks present in the synclines that are formed next to the salt pillows. Mrazec did not believe that these diapirs are either the product of density contrast or "molecular" forces within the salt, the two theories that were put forward by co-workers for similar structures.

Mrazec had several contributions to the understanding of salt tectonics processes that were ahead of his time:

- Viscous flow of salt manifested in salt withdrawal and the flow of salt at surface.

- The importance of overburden thinning before salt break though during salt rise.

- Differential loading as one of the key mechanisms influencing salt flow.

- Plasticity of salt crystals during salt mass flow and the analogy of this to the plasticity of ice crystals and the flow of ice glaciers.

- Development of rim synclines and their expected geometries.

- The diapirs in the Diapir Fold Zone are unrooted and that their feeder is shut (recent nomenclature is salt welds). To our knowledge, this is the first mention of such structures.

Given the limited datasets (wells, outcrops) of the time, it is remarkable that Mrazec put forward an internally coherent salt tectonics model and that some aspects of his model are still valid today.

Following the work of Mrazec, Romanian workers did not have any significant contribution to the development of concepts regarding salt tectonics. All subsequent work faithfully followed the evolution of the international school of thought. Mrazec's ideas were especially out of fashion in the Diapir Fold Zone during the "fluid era" (sensu Jackson, 1995). The "brittle era", has seen the reconsideration of some of Mrazec's initial ideas with some of them now seeming to be a viable model.

The more recent work regarding salt tectonics in the Eastern Carpathian Bend Zone is strongly governed by the availability of data. The data evolved from new wells (more complex well logs) to the use of 2D seismic data (i.e. Ștefănescu et al., 2000) or recently, 3D seismic data. With the advantage of 3D seismic data, new models became available (Schléder et al., 2014, 2016b, *submitted;* Chapter 5). Recently, analogue modelling experiments (Tămaş et al., 2016a, b, 2017a, b, 2018b, *submitted;* Chapter 6) are also contributing to the understanding of salt tectonics in this area.

This paper's chronological overview of concepts in the Diapir Fold Zone (fig. 7) illustrates well the strong influence of (i) available data sets and (ii) the ruling scientific paradigm on scientific thinking.
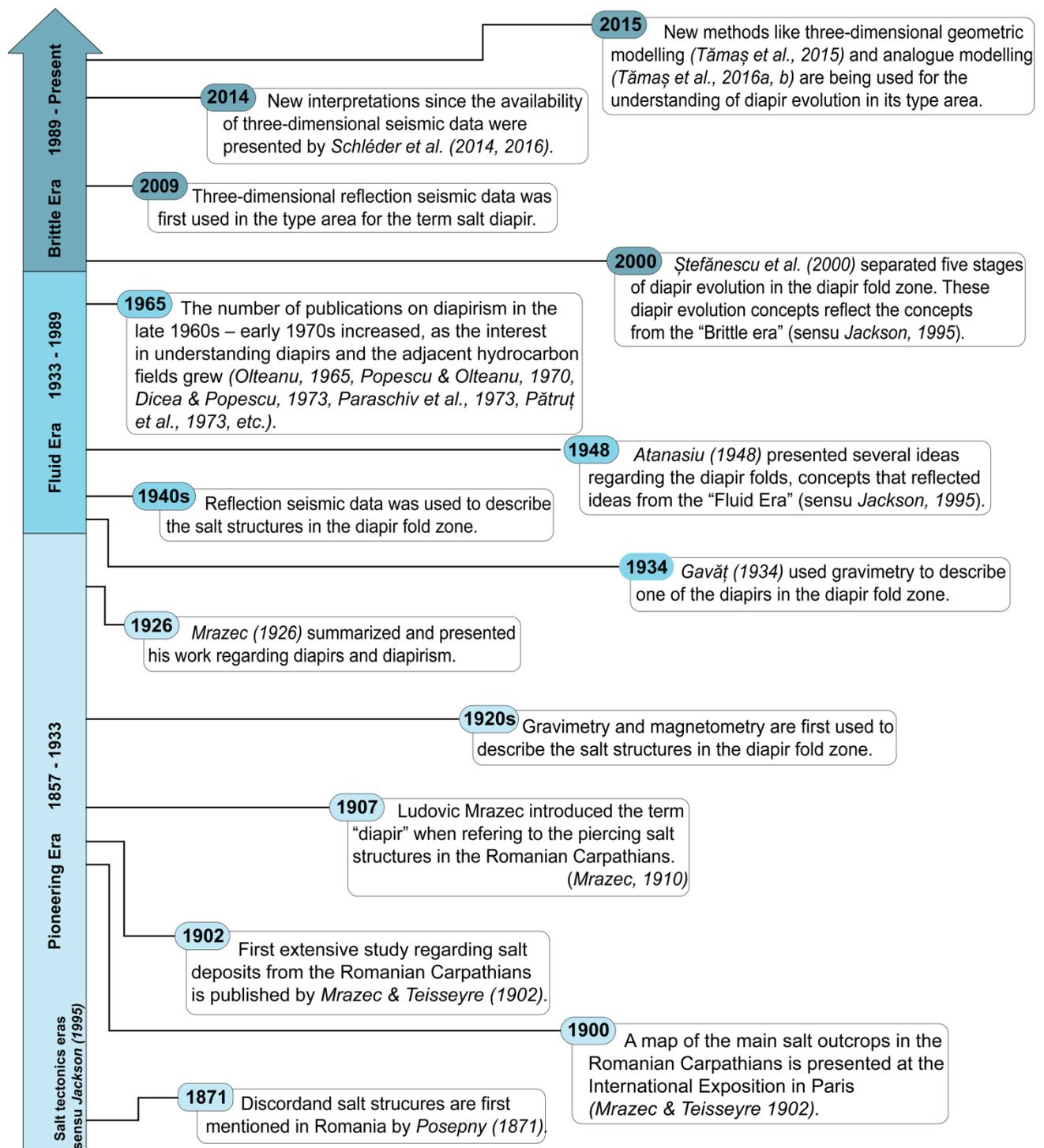
Figure 7. *A chronological evolution of the main concepts regarding salt tectonics in the Romanian Carpathians in the time framework of Jackson (1995) (Tămaș et al., 2018a).*

Chapter 5 - Salt tectonics in the Eastern Carpathian Bend Zone: insights from subsurface data

Chapter 5 deals with understanding the trigger, timing, and development of the diapirs in their type area. The combined results from seismic interpretation, well correlation, geological modelling and 3D structural restoration are used to understand diapirism in the area of interest. The contributions of the latest (Maeotian to Recent) tectonic events to salt tectonics are also treated in this chapter. This chapter also discusses one of the critical features of salt tectonics in the region of interest, specifically its role in the development of the most significant onshore oil fields in Romania. Although the hydrocarbon fields related to the Gura Ocniței – Moreni – Florești – Băicoi - Țintea diapir lineament have a production history of more than 140 years, there are still uncertainties regarding the reservoir compartmentalisation and distribution adjacent to the salt diapirs. Both salt tectonics and the latest (Maeotian to Recent) tectonic events had clear effects on the distribution and compartmentalisation of the Burdigalian, Sarmatian, Maeotian, Dacian and Romanian (Early Miocene to Pleistocene) reservoirs. Understanding these effects may have a tremendous impact in the future field development scenarios of this mature hydrocarbon area, as well as insights into the future exploration potential.

Most of the early historical works done in the CBZ with the scope of understanding salt tectonics and its effects on the hydrocarbon system have been previously based solely on outcrop data. The hydrocarbons related to the diapirs were a focus point almost from the beginning of research in the area, so it was not long until more data came from manually dug wells and the first drilled wells (for more discussions on this topic, see Tămaș et al., 2018a or Chapter 4).

As soon as the well number increased also did the understanding on the reservoirs of the giant fields associated with salt diapirism. For example, the top structure maps of the Viforâta – Gura Ocniței – Moreni – Filipești – Florești –Băicoi – Țintea diapir lineament did not suffer many modifications. The structure maps illustrate the same structural style since the mid-1930s for Viforâta and southern Moreni area (Athanasiu et al., 1935 – 1:125000 map) and since the late 1960s early 1970's for the rest of the above-mentioned fields (Paraschiv & Olteanu, 1970; Paraschiv et al., 1973; fig. 8).
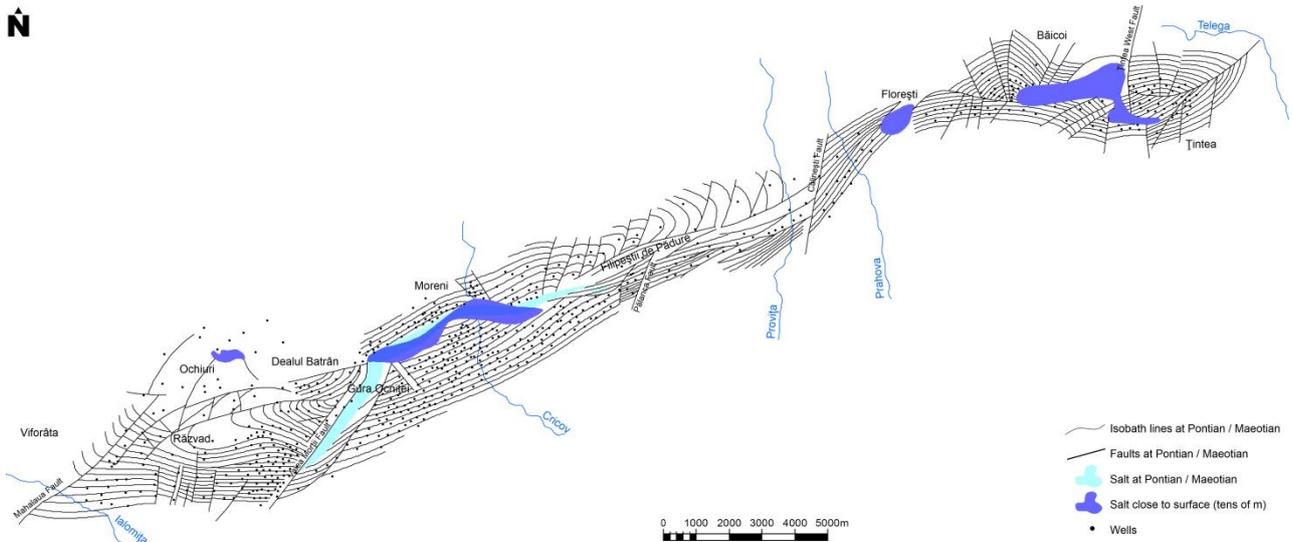
Figure 8. *Top Maeotian (Pontian/Maeotian) structure map from the 1970s. It illustrates the Viforâta – Ochiuri – Gura Ocniţei – Moreni – Filipeşti – Floreşti – Băicoi – Ţintea diapir lineament (after Paraschiv et al. 1973). Note the high well density already drilled at that time.*

The question of how the lower salt survived multiple contraction phases has been a puzzling question for many years that we now try to find an answer to. Another question is: How did the salts journey to the surface affect reservoir deposition and compartmentalization? The current chapter will be a walkthrough of some of the work we did in the search for answers to our questions, using the wealth of existing knowledge (see Chapter 4), results from the analogue modelling experiments (Chapter 6), the extensive well data, the 2D, and the relatively new 3D seismic data.

The access to subsurface data for the realisation of this thesis was granted by the National Agency for Mineral Resources (ANRM) and OMV Petrom (data access was granted for the perimeter presented in fig. 9, at that time part of OMV Petrom exploration blocks, see www.namr.ro for full map). Additional approval was granted for extracting 129 core samples from three wells (fig. 9, wells 36, 64, 65), with the scope of paleomagnetic analysis (see Chapter 7). Part of the work and results of the thesis are subject to the confidentiality clauses and has been excluded from the thesis and any public report (i.e. 3D unfolding, restoration and area misfit analysis of reservoir maps, etc.). Also, according to the agreement, no exact coordinates have been used, and no names and exact locations or depths of the seismic profiles or wells have been included.
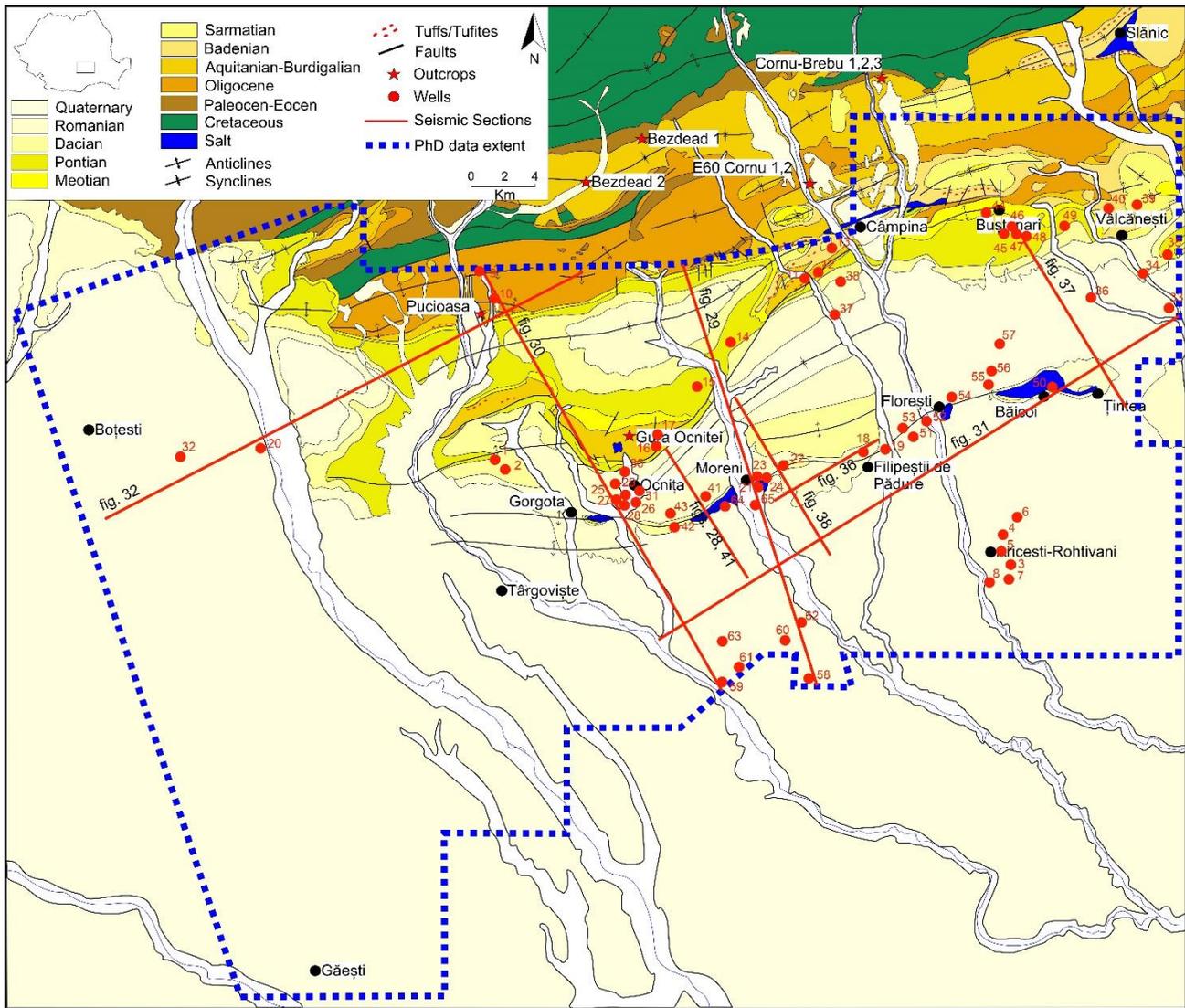
Figure 9. *Simplified geological map of the area of interest. The map also illustrates the perimeter for subsurface data access for this PhD study and thesis with dotted blue line. The wells (red dots) and seismic data (red lines) used in the thesis have the approximate location marked here (map after Murgeanu et al., 1967, 1968).*

The area of interest (fig. 9) is a mature hydrocarbon area with a history of more than 120 years of exploration and exploitation. It is covered by more than 10000 wells (~2% of which reach deeper than 3000m), several 3D seismic cubes (860 km^2 of PSTM seismic), and more than 10000 km of 2D seismic lines. Thus, we can say that the area is ~100% covered by seismic data, 52% of which is 3D data. Most of the well data is old, some having only a basic lithological column, and the majority just SP, deep and shallow resistivity logs (fig. old example). More than 900 of these wells also have core and cutting lab reports. 65 of those wells (fig. 9) have been selected for a biostratigraphic revision (see Chapter 7) in order to clarify some of the well-known uncertainties in the area.

The lithological contacts and structural features (faults, fold axis, dips) digitized from the available geological maps in the AOI were used together with field measurements to aid the interpretations.

In this chapter, an updated story of the evolution of the diapirs in their type area has been presented. The advantage brought by 3D seismic data, coupled with analogue modelling (Chapter 6) and an attempt to revise the biostratigraphic ages in the area (Chapter 7) enabled us not only to have a new perspective of the area but also to test some of these concepts.

Early salt movement might have been present starting with the Burdigalian times, but the initiation of strong salt mobilisation started with the onset of the Badenian – mid-Sarmatian contractional event. During this contraction, salt-cored detachment folds were the main structures created. In the core of these folds, subsalt, a duplex-structure has been envisaged (Schléder et al., 2014, 2016b, *submitted*). As the folds were decapitated during this compression, the salt was free to flow to the surface and might be the source for some of the younger salt (present in the syncline areas). These tight Burdigalian – mid-Miocene folds represent one of the most uncertain reservoirs in the Diapir Fold Zone, mostly because they are poorly images in the seismic data. Some of the uncertainties can be reduced by a rigorous mapping in the syncline area and proper analysis and continuation of these into up to the base Maeotian unconformity.

The Badenian – mid-Sarmatian contractional event was followed by a strong erosion at the base of the Maeotian. Whether we consider the Maeotian stratigraphy as syn-tectonic or that it just fills the post erosion paleorelief is still debatable.

The lower Pontian is with no doubt syn-tectonic, as some of the faults observed in the Băicoi area have lower Pontian growth strata and are also sealed by the upper Pontian. These early Wallachian contractions added a horizontal load on the salt and are interpreted to have increased the rate at which some of these diapirs were rising.

Two different kinematic models are favoured when explaining the Maeotian to recent evolution of the diapirs in the AOI. One implies passive salt rise keeping up with the sedimentation and being controlled by the horizontal load, and the other implies that the salt was buried until the Dacian (covered by Maeotian and Pontian sediments), when it reacted to the opening of small pull-apart basins and raised to the surface.

The salt was squeezed in its present-day position by the last of the Wallachian contractions (which were also more significant than the early Wallachian ones). Understanding the present-day shape of the diapirs not only enhances our understanding of its evolution but also reduces risks related to drilling through salt.

Chapter 6 - Salt tectonics in the Eastern Carpathian Bend Zone: insights from analogue modelling

Part of the work presented in this chapter is published in the paper: Tămaş, D.M.; Schléder, Z.; Tămaş, A.; Krézsek, C. Copoţ B. and Filipescu, S., submitted, Middle Miocene evolution and structural style of the Diapir Fold Zone, Eastern Carpathian Bend, Romania: insights from scaled analogue modelling, In: Hammerstein, J., Di Cuia, R., Griffiths, P., Cottam, M., Zamora, G., and Butler, R. eds, Fold and Thrust Belts; Fold and Thrust Belts: Structural Style, Evolution and Exploration, Geological Society of London, Special Publications. permission of the Geological Society of London is required for further use.

Insights from analogue modelling (eg. fig. 10, 11) have often been used to aid in understanding structural complex geological settings. Chapter 6 examines the results from scaled analogue modelling experiments that were conducted during this research. The chapter treats topics like the details of diapirs which possibly rose through vents opened by pull-apart basins, the effects of lower decollement rheology and intermediate decollement thickness on the development of the detachment folds and sub-salt duplexes, and discusses the kinematic evolution of the diapirs in the DFZ.
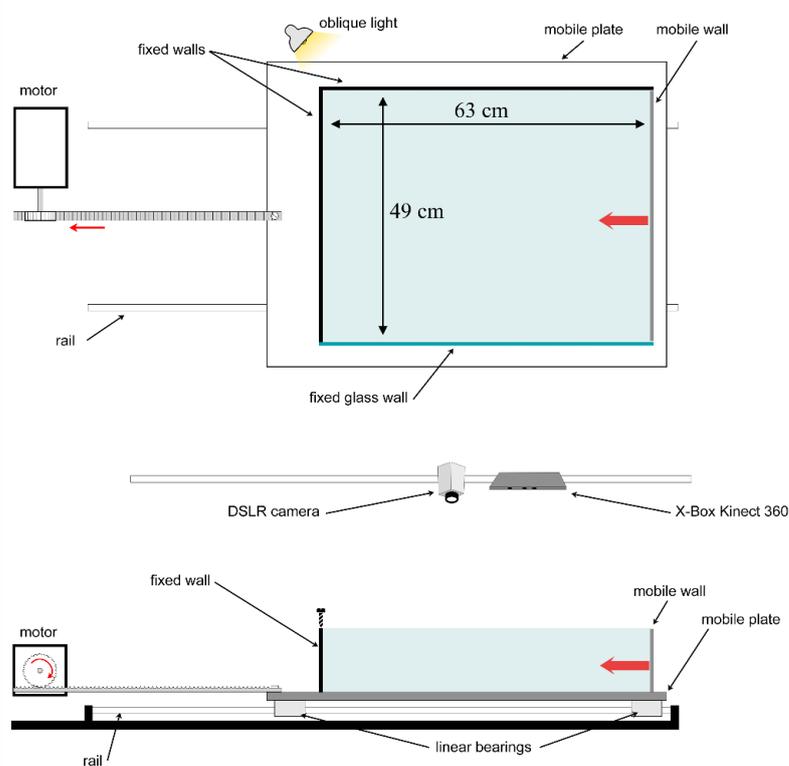

Figure 10. Diagram of analogue modelling apparatus used for compression. The topview (A) and sideview (B) illustrate the stepper motor-driven base mobile plate that slides on the rails, beneith the fixed walls. The top-view experimenta monitoring is achieved using the DSLR camera and the X-Box Kinect 360 (infrared projector and camara), illustrated on the sideview diagram (B).

Schléder et al. (2014, 2016b, *submitted*; Chapter 5) propose two possible kinematic models for the evolution of the salt diapirs during the Maeotian to recent times. One of them states that the diapirs in this area rose through vents opened by small pull-apart basins (1.5-2 km across; see Chapter 5 for details). Two main topics were investigated through analogue modelling: the amount of dextral strike-slip movement needed for a diapir to reach the surface and pierce through the analogue equivalent of 800 m of sediments and the effect of the releasing-bend stepover angle on the evolution and shape of the diapir. The results show that the stepover angle was a major factor influencing both the shape of the resulting diapir and the amount of strike-slip movement needed for the diapir to reach the surface. While in the model 1.1 (30° stepover angle), the diapir had a bell-shape and a total of 3.6 cm of strike-slip movement for the diapir to reach the surface, in model 1.2 (45° stepover angle), the diapir had a mushroom shape (i.e. similar to the Băicoi) and 2.4 cm of strike-slip movement was enough for it to reach the surface.

The other proposed kinematic model is that salt continued to rise during the Maeotian to recent times and the rate at which this happened was actively controlled by the compressional events that created horizontal load on the salt. This model was investigated in experiment 2.7. Although the final sub-salt geometries in this model were a bit exaggerated due to the high initial erosion, the evolution of the experiment after the "Maeotian" was relevant to our topic. We observed that salt slowly continued to rise after cessation of compression and that the rate increased with each compression that was applied. Not only did the rate at which the salt was rising increased, but as some preexisting faults were reactivated, some buried diapirs were rejuvenated and started to rise solely as a result of the applied horizontal load. This experiment confirms that this is also a valid kinematic model for the evolution of these diapirs and brings insights into how the reservoirs were affected.

In order to better understand the effects of the rheology of the lower decollement and salt thickness in the development of the spaced ramp-anticline duplexes and overlying detachment folds, a series of analogue modelling experiments have been performed. Results from these experiments show that decreasing the basal friction will change the geometry of the sub-salt duplexes from prograding monocline (no base decollement), to spaced ramp-anticline (glass microspheres) and to a long wavelength forward breaking piggy-back thrust sequence (silicone) (see also Couzens-Schultz et al., 2003 for more details).

The space between the duplexes was also affected by the silicone thickness (along with the supra-salt deformation). As the coupling between the supra- and sub-salt increased the sub-salt duplexes became more spaced, and the supra-salt deformation became more characterised by

detachment folding rather than faulting. The faulting occurred in most of the cases after the formation of the detachment fold. The deformation in the supra-salt layers localised more above the sub-salt duplexes as the coupling increased.
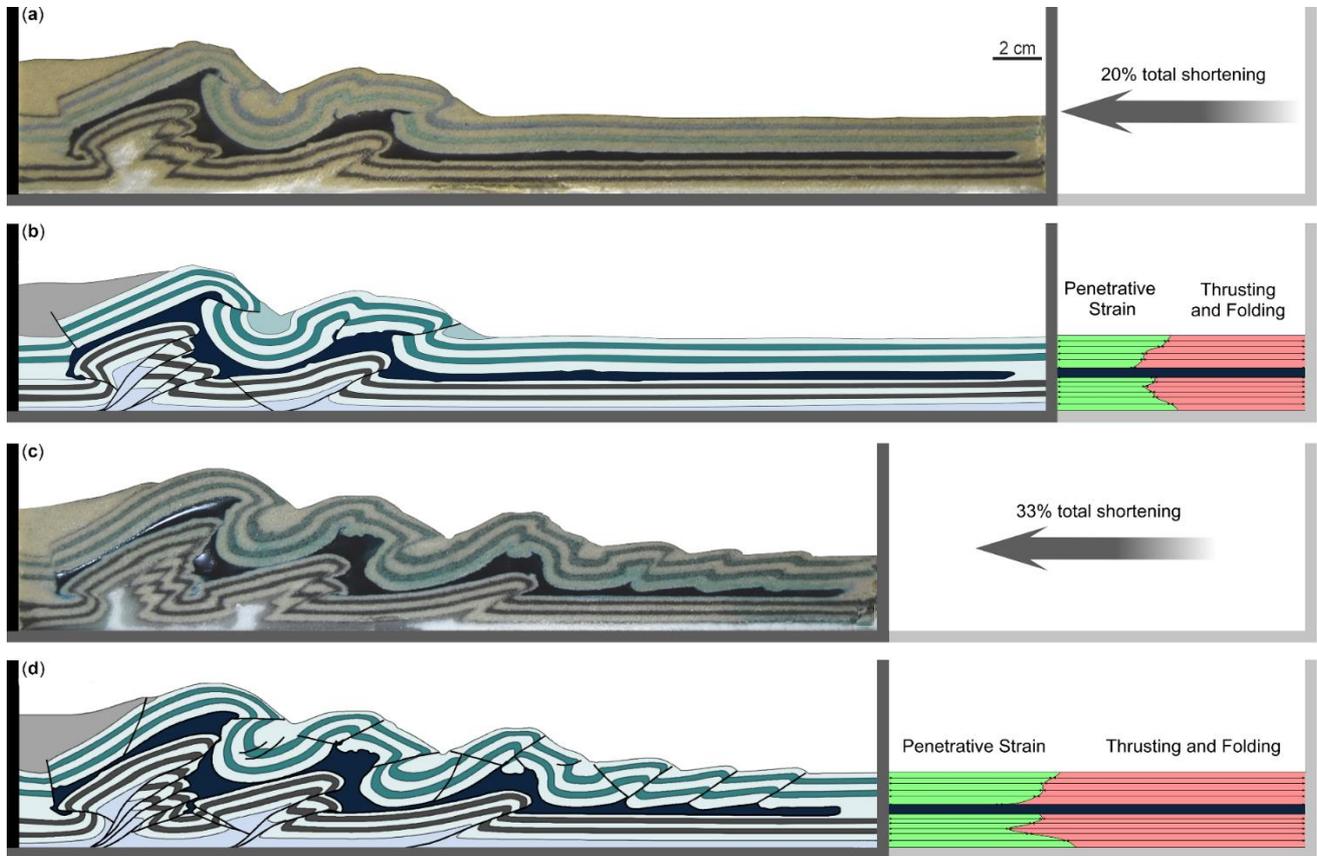
Figure 11. *Cross-sections through analogue models 2.5 and 2.6, located in the central area of the experiments. Model 2.5 (first section (a) - uninterpreted and second section (b) - interpreted) has a total shortening of 20 %, while model 2.6 (third section (c) - uninterpreted and forth section (d) - interpreted) has a total shortening of 33 %. On the right of each interpreted sections (b, d) the total contribution of penetrative strain (green), thrusting and folding (red) is illustrated.*

The deformation style interpreted in the analogue modelling experiments show a high geometric similarity to the supra-salt structures that can be observed on the 2D and 3D seismic data in the DFZ (Chapter 5; fig. 12). This leads us to have more confidence also in the sub-salt deformation style. The results are comparable with the most recent structural interpretation in the area (Chapter 5). Thus, we believe that both the style and timing of structure development is similar to that in the DFZ. This provides further insights into the geometry of the fold-and-thrust belt in the areas poorly images on seismic (near- and sub-salt; fig. 12c).
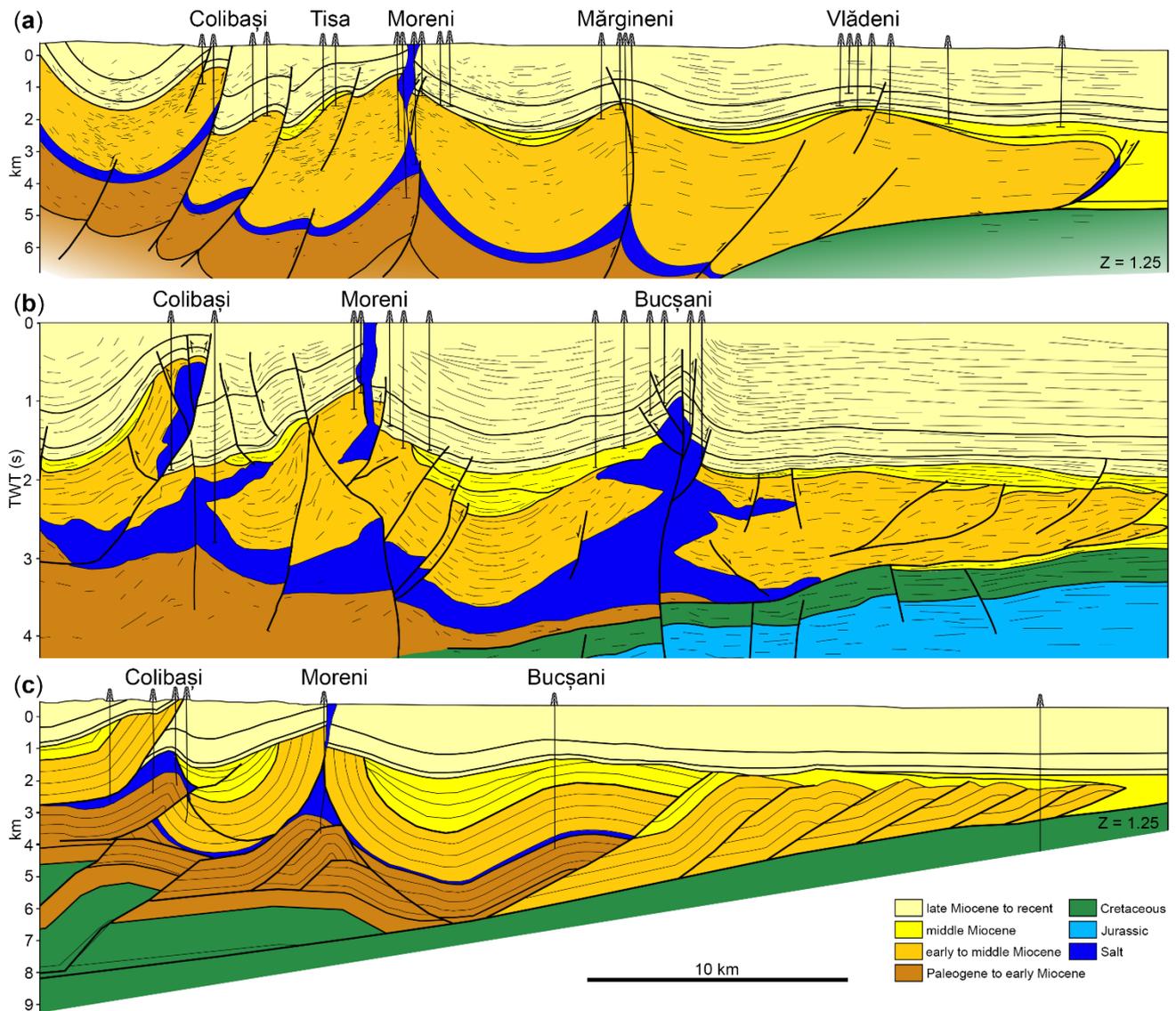
Figure 12. Geological cross-sections through the Diapir Fold Zone, illustrating some of the different structural styles proposed for the area. (a) cross-section mainly based on well and surface data with some early seismic data (Hristescu and Olteanu 1973; Pătruț et al. 1973; Tămaș et al. 2017). (b) composite geological cross-section built based on 2D seismic and well data (Ştefănescu et al. 2000; Tămaș et al. 2017). (c) Interpretation based on 3D, 2D seismic and well data by Schléder et al. 2016. This section represents the most recent interpretation in the area. [Note that cross-sections (a) and (c) are in depth and (b) is in two-way time (TWT)]

Two analogue modelling experiments (models 2.5 and 2.6, with 20% and respectively 33% shortening) have been performed with the scope of understanding the middle Miocene deformation style in the DFZ. Both models are highly relevant to the structural evolution of the area, model 2.5 (20% shortening; fig. 11a, b) representing an intermediate stage during this deformation. Model 2.6 (figs. 11b - 8) is the most relevant to the deformation style in the DFZ, as it presents all the main structural lineaments in the area. The first sub-salt duplex lineament and axis of first detachment fold (from the backstop) is comparable with the case of Colibași and Runcu-Buștenari structures (see Chapters 2-5; fig. 12). The second sub-salt duplex and corresponding detachment fold are

representative for the most important hydrocarbon lineament in the area, the Gura Ocniței – Moreni – Filipești – Călinești – Băicoi – Țintea (see Chapters 2-5; fig. 12). The sub-salt duplex corresponding to this lineament just started to develop at 16-20% shortening (fig. 11). The third detachment fold in model 2.6 (fig. 11c) is representative for the Bucșani – Mărgineni – Aricești lineament (see Chapters 2-5; fig. 12), while the rest of the supra-salt deformation is related to the rest of the lineaments until the pericarpathian line (see Chapters 2). Most of the lineaments that developed during this deformation phase are later reactivated during the Wallachian deformation and generate the structures that are visible on the map.

The deformation style interpreted in the analogue modelling experiments show a high geometric similarity to the supra-salt structures that can be observed on the 2D and 3D seismic data in the DFZ. The broad detachment folds with very tight limbs in the supra-salt are lower to middle Miocene in age and represent some of the most poorly imaged and understood reservoirs in the area, due to their high dips and proximity to the salt (Ștefănescu et al., 2000; Schléder et al., 2016b, *submitted*; Tămaș et al., 2018a). The deformation style of these detachment folds, the presence of out of syncline thrusts, multiple shear thrusts and the significant contribution that layer parallel shortening has on these reservoirs bring essential insights that are useful in both seismic interpretation and reservoir modelling.

The high geometric similarity between the supra-salt deformation in model and nature leads us to have more confidence also in the sub-salt deformation style. The results are comparable with the most recent structural interpretation in the area (Chapter 5; fig. 12c; Schléder et al., 2016b, *submitted*). The sub-salt duplexes are located directly beneath the axis of the long wavelength detachment folds, as the development and geometry of these folds was actively controlled by the development of the sub-salt duplexes. The reduction in salt thickness in the axis of the supra-salt synclines increased the coupling (drag), between the supra- and sub-salt sequences, causing an increase in the distance between the duplex structures. We believe this is also the case in the DFZ, as the sub-salt duplexes seem to be located just between the broad supra-salt synclines (see Chapter 5; fig. 12c).

Although some syn-kinematic sedimentation and erosion have been active during the mid-Miocene compressional event (which was the focus of these models), it was not included in the modelling procedure. It is well known that syn-kinematic sedimentation and erosion play an important role on the structural styles, and this has also been studied using analogue modelling (Storti & McClay, 1995; Pichot & Nalpas, 2009; Konstantinovskaya & Malavieille, 2011; Wu & McClay, 2011). The addition of syn-kinematic sedimentation and erosion during the mid-Miocene contractional event is

expected to have increased the wavelength at which the detachment folds would have developed and implicitly the distance between the sub-salt duplexes (e.g. Wu & McClay, 2011).

As mentioned above, quantifying the amount and variation of penetrative strain in our models was another topic that was addressed. Previous analogue modelling studies done in purely brittle accretionary wedges (Koyi, 1995; 2000; Koyi et al., 2004) show that the penetrative strain dominates the deformation at depth, results also replicated in other studies (e.g. Burberry, 2015). The results from analogue modelling studies on penetrative strain involving ductile materials are contrasting. Koyi et al. (2004) still mentioned an increase of penetrative strain with depth above a ductile decollement and Lathrop & Burberry (2017) suggested that the penetrative strain decreases with depth to reach near zero values at the surface of the ductile decollement.

Above the salt, our experimental results show a small decrease of penetrative strain with depth, supporting the results of Lathrop & Burberry (2017) of decreasing penetrative strain above a ductile decollement, but not to a value of 0% above it. As the salt is virtually incompressible below a certain depth, no significant volume change will take place within it (Jackson & Talbot, 1986; Weijermars et al., 1993; Jackson & Hudec, 2017), but it is still able to accommodate and influence the layer parallel strain, both in the supra- and sub-salt layers.

Below the salt, we expected for penetrative strain to increase towards the base of the models, as mentioned in purely brittle experiments (e.g. Koyi et al., 2004; Burberry, 2015). The increasing layer parallel shortening with depth above a glass microsphere detachment has been documented by Koyi et al. (2004). Our results differ from the published experiments as the first values measured below the salt are slightly higher and first decrease with depth and then increase towards the base of the experiment. We believe that this is due to the effect of salt flow on sub-salt deformation, but this phenomenon needs to be systematically investigated. Layer parallel shortening within the glass microsphere detachment has not been measured but is expected to be lower, as Koyi et al. (2004) results, which they attributed to the different nature of the lithology.

The main take-away messages from the experimental part of the thesis are:

(1)   Scaled sandbox analogue modelling coupled with time-lapse photography, particle image velocimetry and digital elevation modelling can accompany and aid seismic interpretation and predict subsurface geometries in the poorly constrained areas. The seismic quality in the Diapir Fold Zone is strongly affected by the presence of salt. Results offered by the analogue modelling

experiments help to better predict reservoir geometry and deformation both near and beneath the salt bodies;

(2)   Our compressional models present a structural style characterised by features of spaced sub-salt duplex structures. These sub-salt duplexes are overlain by wide supra-salt detachment folds with steep limbs (up to vertical). The structural style of these analogue modelling experiments confirms the latest interpretations (see Chapter 5; fig. 12c);

(4)   The two possible kinematic models for the evolution of the diapirs that have been presented in Chapter 5 have been investigated using analogue modelling experiments. Each of these two models has been confirmed to be possible, and the implications for each of them on reservoir deposition and compartmentalisation have been taken into account. It is highly possible that the evolution of the diapirs in this area to be a combination of both kinematic models put forward.

(5)   The penetrative strain is an important feature in fold and thrust belts. Although the means by which it affects analogue models and nature is different, the models offer important details regarding its temporal and spatial distribution. As the total amount of shortening increases (in time), the contribution of penetrative strain decreases. The same results have already been noted in other analogue modelling studies (e.g. Koyi et al., 2004; Burberry, 2015). Penetrative strain decreases with depth above the salt level, but below it initially decreases and then increases towards the base of the models (sections).

(6)   The analogue modelling results shed more light on the early salt tectonics, the evolution of subsalt duplex structures, detachment folds and the possible Maeotian to recent evolution of these diapirs. Our models could be used as a template for interpreting areas with poor quality seismic near and sub-salt structures.

Chapter 7 - Preliminary stratigraphic re-evaluation of existing core and cutting data

Some of the stratigraphy in the CBZ presents high uncertainties and also the age of salt is not a closed topic. As such, in Chapter 7, we present preliminary results of a biostratigraphic and chronostratigraphic reevaluation of core and cutting data from the DFZ. A total of 65 wells with extensive lab reports from cores and cuttings have been chosen. The biostratigraphy identified in these lab reports was carefully re-interpreted and integrated with 2D and 3D seismic data. Also, the cores of three wells have been sampled for paleomagnetic analysis, two of which provided good results.

The Diapir Fold Zone (DFZ; fig. 13) is a highly mature hydrocarbon area with a production history of more than 130 years. Although the area has a long history of operations and an immense quantity of data (see Chapter 4), the stratigraphic framework in the hydrocarbon industry of this area is outdated and has not been re-evaluated according to the recent developments in both the international and regional stratigraphy. There is a need for revision mainly for the Oligocene-Miocene record, where the industry formal or informal stratigraphic units are outdated (see Munteanu et al., 2014; Bercea et al., 2016a, b for a similar discussion).
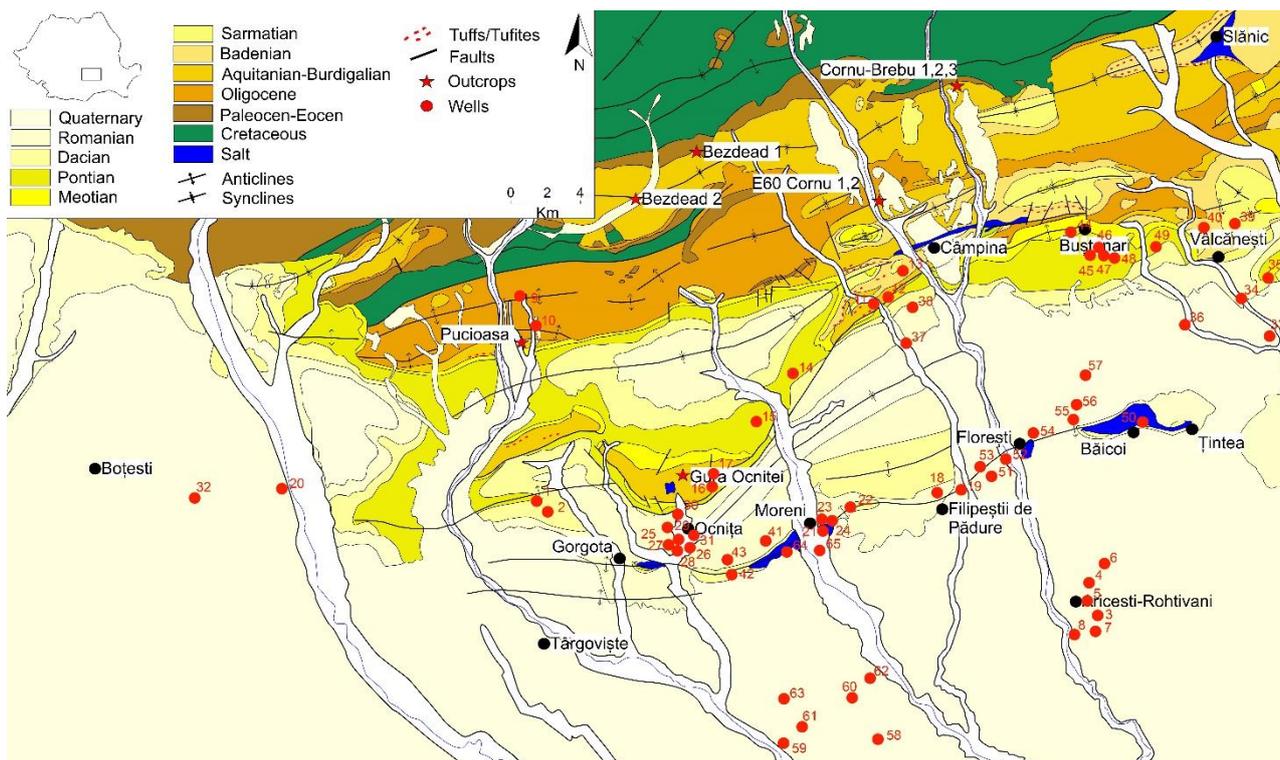
Figure 13. *Simplified geological map of the Diapir Fold Zone (modified after Murgeanu et al., 1967, 1968). The image also illustrates the approximate location of the 65 wells, the location of the Pucioasa section and other studied outcrops outcrops (Bezdead, Ocnița, Cornu de Sus and Brebu).*

As this study is primarily based on a reinterpretation of existing micropaleontologic reports made for the old wells' cores and cuttings, there is an obvious degree of uncertainty. This uncertainty was reduced by the integration of outcrop data. Moreover, both the old well and outcrop data were integrated with 2D and 3D seismic data, which further reduced the uncertainty of the revised stratigraphic model (Chapter 5). This type of re-evaluation is essential because most of the published interpretations and also some of the kinematic evolution interpretations/models have been based on the "traditional" stratigraphy.

The uncertainties regarding the stratigraphy of the Oligocene to lower Miocene have been highlighted long before this study (see the discussions regarding the age of salt in Chapter 4).

Athanasiu (1916) did not believe there is clear biostratigraphic evidence for even the presence of the Aquitanian and Burdigalian and their identification is highly uncertain because the taxa used to define them have higher ranges, up to the middle Miocene. Also, for most of the Oligocene and lower Miocene ages reported in this area, palynology played a key role, even if the results bared high uncertainties, as discussed below.

Since the early times of exploration, biostratigraphy has been one of the key factors for the stratigraphic and subsequent interpretations. Unfortunately, due to the particular facies, the expected index fossils could not always be found. For this reason, at certain intervals, the biostratigraphy has been based on irrelevant or facies depending endemic assemblages. Moreover, the locally developed biostratigraphic schemes have been subsequently used for interpretations on basin and tectonic evolution.

Recent reevaluation of field material in some areas (Szabo & Filipescu, 2010; Szabo et al., 2010, 2011; Bercea et al., 2016a, b) revealed the need of a serious stratigraphic revision of the previously considered Oligocene to middle Miocene interval. This revision should consider the recent developments in taxonomy and biostratigraphy, as necessary tools for an update of the biostratigraphy used in the oil industry and research originating in the early and mid-20th Century.

Below are presented some of our preliminary results both from the core and cutting stratigraphic re-evaluation and from the outcrop data. We also highlight the most uncertain ages and present a possible new interpretation of some seismic profiles. In the end we discuss possible implications of the encountered age differences and a way forward of the continuation of this study. As the topic of this thesis is not palaeontology or biostratigraphy, the taxonomic details regarding this evaluation have been omitted and will only be discussed in the paper, once it will be submitted and published.

The upper Miocene to recent stratigraphy did not present any major issues, but we were able to go into a greater detail and perform a magnetostratigraphic analysis on Maeotian, Pontian and Romanian core samples.

From the 626 revised core and cutting descriptions, only 36% yielded similar results the originals (fig. 14A; appendix 2). The rest were different, either giving a broader stratigraphic range or a different age (fig. 14B; appendix 2). When combining the results from the different groups, special care was taken in the cutting descriptions and the position of the casing shoe at the time of sampling, thus reducing the possible influence of sample contamination.
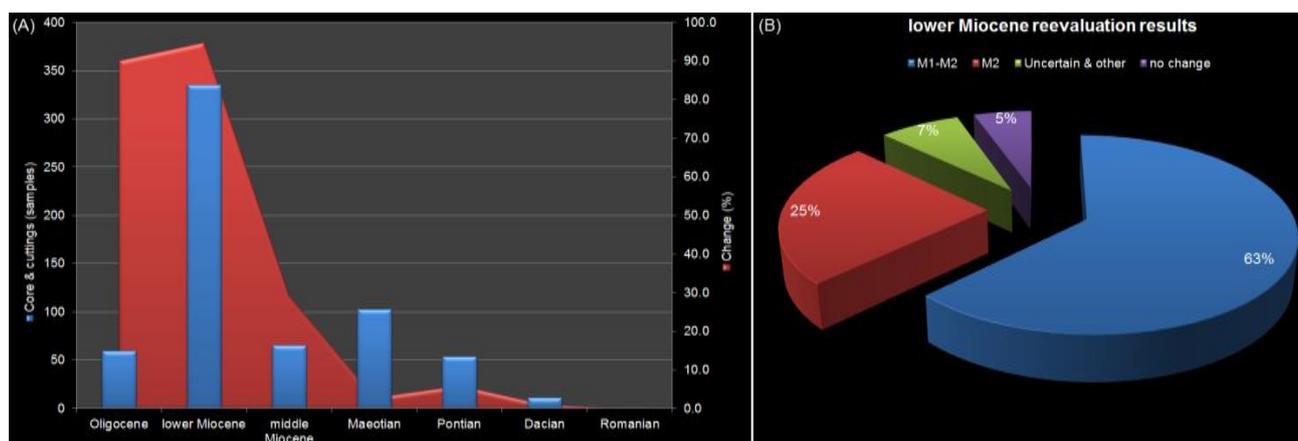
Figure 14. *Statistics of the biostratigraphic reevaluation results.*

Due to the complex tectonic evolution of the Carpathian domain during the Oligocene and Miocene, several stratigraphic intervals contain endemic or very scarce fossil assemblages, which make the age determination sometimes very difficult. This paleogeographic evolution produced severe restrictions of the connections to the open sea in most basins in the Carpathian domain, and this way it is difficult to find typical index taxa for the Oligocene – Miocene boundary and for the early part of the Miocene.

Excluding the well-known problem of the lower Miocene, upper Kliwa unit being still called "Oligocene" by some hydrocarbon companies (i.e. Munteanu et al., 2014; fig. 14A, where 90% of the Oligocene encountered had younger ages), most changes occurred in the lower Miocene (fig. 14; 95% difference with respect to the old interpretations).

The stratigraphy previously interpreted as lower Miocene usually contains a lot of reworked Paleogene and Cretaceous material. Most often, the revised age of the analysed cores had a longer interval, and the specific age could not be determined.

The integration with the 3D, seismic-based model mitigated conflicting results between the different biostratigraphic groups. Also, in most of these cases, the younger interpreted age was taken

into consideration (mainly from the foraminifera), mostly due to the high reworking suffered by the other, very small sized, biostratigraphic groups (calcareous nannoplankton and palynology).

The resulting stratigraphic evaluation not only reveals the stratigraphic units with the highest uncertainty but also allows for a possible age reinterpretation. This leads to an alternative stratigraphic model for the area and may open new opportunities in this highly mature hydrocarbon area. The structural evolution history is also affected as some of the interpretations are solely based on the old stratigraphic framework.

Within the less uncertain stratigraphy, the re-evaluation enabled us to gain more detailed biostratigraphy and for some ages (Maeotian and Romanian), even perform a more detailed, magnetostratigraphic study. This enabled us to interpret the age of the first Maeotian sediments that were deposited (in the Moreni diapir area; fig. 13) on the base Maeotian unconformity as taking place at about 7.6 Ma (in line with recent studies; Palcu et al., 2018). The studied intervals from the Maeotian range from 7.65 to 6.1Ma and had an average sedimentation rate of ~20cm/kyr. The Romanian samples allowed us to confirm the age but did not bring a high detail as multiple erosional features make it hard towards impossible to perform a detailed interpretation. The sedimentation rate during the Romanian was surely >20cm/kyr.

Even if this study is mainly based on the reinterpretation of earlier identified taxa (the primary data not being available anymore), this approach is highly recommended for most areas due to its potential for improving the stratigraphic resolution and aiding in the construction of structural and depositional environment models. For a complete and reliable stratigraphic reevaluation, resampling and proper identification / interpretation of the micropaleontological record is mandatory.

In most of the cases, the highly uncertain strata were previously interpreted as Oligocene and lower Miocene. Our recent investigations show that a good part of the Oligocene in these wells can be reassigned to the lower Miocene, and the lower Miocene is either hard to be separated or has been reinterpreted as middle Miocene. There is certainly more middle Miocene stratigraphy between the top of the salt layer and base Maeotian unconformity than initially interpreted (see Chapter 3; Schléder et al. *submitted*; Chapter 5). Seismic interpretations presented in the thesis (Chapter 5) follow our most recent results and now present part of the stratigraphy earlier interpreted as lower Miocene to be middle Miocene.

Chapter 8 - Conclusions and future work

The objective of this thesis was to gain a better regional and sub-regional understanding of the kinematic evolution of the diapirs in the Diapir Fold Zone. Several questions meant to fulfil the objective have guided the shape and results of this thesis:

- How the modern-day understanding of the diapirs in the DFZ came to be?
- What were the historical models regarding the kinematic evolution of these diapirs?
- What were the main factors controlling the structural style?
- Can we understand more about the effects of basal decollement efficiency and salt thickness on the kinematic evolution of the diapirs in the DFZ?
- What is the geometry of the sub-salt structures? Can we use analogue modelling to predict this?
- Is the traditionally used stratigraphy (mostly in the hydrocarbon industry) still correct?
- Can we have a better time correlation of some events (i.e. the base Maeotian unconformity)?
- How did these diapirs evolve and what was the trigger and timing of their rise?
- What is the 3D geometry (size and shape) of these diapirs? Can these be mapped in more detail?
- Is it possible to understand more regarding the post-Sarmatian tectonic events in the area with the available data?
- Did diapirs and diapirism have any effect on reservoir distribution and compartmentalisation?

Researchers studying salt tectonics in Romania played and important role in the history and the development of new concepts regarding salt deformation and tectonics. We can say that the history of salt tectonics in Romania began with the work of Posepny (1871), who was not only the first to describe discordant salt structures in the area but also observed and illustrated features that are still valid today (ductile salt, rim-synclines, upturned flaps, etc.). Following this, Ludovic Mrazec had key contributions, not limited to describing the structures and coining the term diapir, but he was the first to put forward an internally coherent sale tectonics model, describing some aspects of salt tectonics that are still valid today.

Mrazec also had many contributions that were ahead of his time, like describing viscous salt flow, salt withdrawal, salt free flow at the surface, the importance of overburden thinning and

differential loading, the plasticity of salt crystals, development of rim synclines, salt welds, etc. The more recent work in salt tectonics in the DFZ being governed by data availability and as the data evolved to more complex well logs, 2D seismic data, and more recently 3D seismic data.

For this thesis, the available sub-surface data (3D and 2D seismic reflection data and well data) was coupled with analogue modelling in order to gain a better understanding regarding salt tectonics in the Diapir Fold Zone.

Results have shown that the first significant mobilisation of salt in this area, took place during the Badenian – mid-Sarmatian contractional event, when the deformation style was characterised by detachment folding in the supra-salt stratigraphy and salt flow towards the crestal parts of the anticlines. Sub-salt duplexes are interpreted to have developed in the core of these folds. As these crests of these supra-salt anticlines were being eroded, salt was exposed to the surface and was free to flow.

As this mid-Miocene deformation represents the main deformation in the area and the information provided by seismic imaging is limited due to its poor quality in the proximity of the salt and sub-salt, analogue modelling experiments have been performed. The results from these models (section images) coupled with time-lapse photography, particle image velocimetry and digital elevation modelling aided the seismic interpretation and helped predict subsurface geometries in the poorly constrained areas.

The effects of the presence and type of base decollement, as well as the thickness of salt, have been investigated by means of analogue modelling, and the results provided insights into the structural evolution of the Diapir Fold Zone, the sub- and supra-salt deformation and it is on these experiments that we identified the important contribution that penetrative strain has in the deformation.

Although the means by which penetrative strain affects analogue models and nature is different, the models also offered important details regarding its temporal and spatial distribution. As the total amount of shortening increases (in time), the contribution of penetrative strain decreases. Penetrative strain decreases with depth above the salt level, but below it initially decreases and then increases towards the base of the models.

The Badenian – mid-Sarmatian contractional event was followed by a strong erosion at the base of the Maeotian, afterwards followed by a Maeotian to recent contractional event (Wallachian). The character (syn-tectonic or not) of the Maeotian stratigraphy is hard to identify, and the topic is still

up for discussion, at least in the studied area, while the Pontian to recent stratigraphy is without a doubt syn-tectonic. These early Wallachian contractions added a horizontal load on the salt and are interpreted to have increased the rate at which some of these diapirs were rising.

The Meotian and younger kinematics of the salt diapir growth can be explained in at least two different kinematic models. One sees the burial of the salt until the Dacian and its subsequent rise in local releasing bends due to right-lateral strike slip in the area. The alternative model suggests that the salt rise kept up continuously with the sedimentation and halokinetic sequences formed at the salt-sediment interface. Both of these scenarios have been tested using analogue modelling experiments and are equally possible. Moreover, these analogue modelling experiments provided information regarding the expected deformation style for each of the two scenarios.

The salt was squeezed in its present-day position by the last of the Wallachian contractions (which were also more significant than the early Wallachian ones). Understanding the present-day shape of the diapirs not only enhances our understanding of its evolution but also reduces risks related to drilling through salt. For this, a 3D model of the Moreni diapir was constructed using the seismic data (although of poor quality near the diapirs and sub-salt), coupled with the extensive well data was used.

Another important topic briefly addressed by the thesis is the uncertainty regarding the age of the stratigraphy in the studied area. The work done for the biostratigraphic and chronostratigraphic reevaluation in the DFZ revealed that the age interpretations for the Oligocene and lower Miocene bare high uncertainties. Most of the Oligocene has been reinterpreted as being lower Miocene in age, but this is a fact that was already highlighted in previous studies.

The most uncertainties lie in the lower Miocene formations, where the majority of the reevaluated core and cutting biostratigraphic interpretations were either impossible to separate from the Miocene in general (lower and middle) or were reassigned to the middle Miocene. We now consider a large part of what was initially interpreted to be lower Miocene as middle Miocene. These preliminary results lead to an alternative stratigraphic model for the area and may open new opportunities in this highly mature hydrocarbon area.

For the less uncertain stratigraphy (upper mid-Miocene to recent) we were able to further increase the detail of interpretation and to narrow the biostratigraphic interpretations for many studied intervals. For the intervals with more recent cores (Maeotian and Romanian), we were able to perform a magnetostratigraphic study, which further increased the resolution of our data and offered valuable

information regarding the timing of events (first Maeotian sediments in the Moreni diapir area) and regarding sedimentation rates.

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