

Geodynamical comparative study regarding the salt domes of two different depositional environments: Mexico and Romania

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Abstract: Salt diapirs are geological formations that appear in the subsurface and are formed over millions of years. Such formations occur due to the density difference between the salt and the surrounding rock. The density difference causes the salt to penetrate throughout the strata and, therefore, the salt rises to the surface in a process known as diapirism.

The importance of salt domes, structures that form because of diapirism, lies on the fact that due to the impermeability of the salt and the deformation associated with the ascent of these structures, salt domes become excellent oil traps, with important reserves. Therefore, it is important to know the conditions that dominate the development of salt domes as well as their evolution and formation environments.

If the subsurface is considered as a continuum and by means of the momentum equations, Newton's second law and the heat conservation equation, in addition to an Eulerian approach to matter, numerical models showing the evolution of salt domes can be created, and thanks to them, the parameters that influence the formation of the domes can be calculated.

In this work it is concluded that some of the parameters that determine the formation and ascent of the diapir are the width and height of the initial Gaussian anomaly, the viscosity of the salt, the temperature, and the thickness of the salt layer.

Keywords: Diapirism, Prahova, Subcarpathians, Romania, Mexico.

1. INTRODUCTION

Various salt structures including salt diapirs represent an important economic interest, both for their nature as sources of salt for industrial use, as well as the relationship of these structures with other resources, specifically hydrocarbons, whose importance is indisputable. Salt diapirs are a mass of salt, which flows with a ductile behavior (from a geological standpoint) in discordance with the overburden (Jackson & Hudec, 2017a; Mrazec, 1907; J. Warren, 1999). Both in Mexico and Romania there are important oil and gas resources related to these structures; some of the most important hydrocarbon provinces in the world are located on salt basins, for example the Gulf of Mexico, the Persian Gulf, the North Sea, the lower Congo basin and the Precaspian Basin (Jackson & Hudec, 2017c; J. Warren, 1999; Tămaș, 2018).

2. AIMS AND OBJECTIVES

The main objective of this paper is to compare two large salt deposit provinces where it is possible to observe the phenomenon of salt tectonics in the form of salt domes and salt diapirs. The salt basins where the study was performed are “La Popa” basin located in the north of Mexico and the eastern Carpathian bend zone in Romania. This comparative study aims to contribute to the search for a better understanding of the geodynamical behavior (spatial and temporal evolution) of salt diapirs. To accomplish this task numerical tools are used to analyze the geodynamic evolution of salt domes in both regions.

3. ABOUT SALT DOMES AND SALT DIAPIRS

In addition to the evidence provided by the salt diapirs on the plastic behavior of rocks, salt diapirs

are of great importance in structural geology. These geological structures can have different shapes because of the previous formation of a diapir. In general, salt diapirs are formed by the buoyancy force generated by the difference in salt densities when salt is buried beneath more types of sediments (Figure 1). Because of its low density compared to adjacent rocks and overburden, salt tends to flow upward, thereby forming domes (i.e., the structure formed by the uplift of a salt core and its covering of deformed layers, Harris & Veatch, 1899) layers, pillars, and other structures (Figure 2).

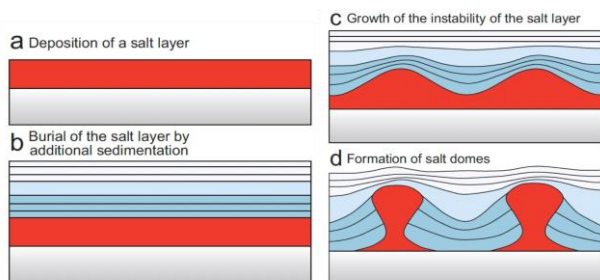


Figure 1. Phases of the formation of a salt diapir

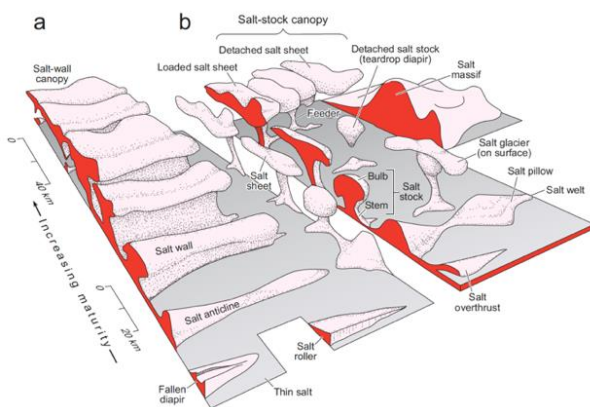


Figure 2. Common structures in salt diapirs
(M. P. A. Jackson & Talbot, 1986)

Usually in tectonically unactive areas, the rise of salt domes occurs only at the surface due to the density difference (downbuilding), since the density of salt is approximately 2.2 g/cm³, which makes it less dense than the overlying rocks (2.5-2.7 g/cm³) (Jackson & Hudec, 2017c). However, due to tectonic movements, the salt mass can flow along faults and produce a great diversity of different types of structures. The saline basins where diapirism takes place in Mexico are: The “*Salina*

del Istmo” basin, The “*La Popa*” basin and the “*El Perdido*” Folded Belt, as well as the Eastern Carpathian bend zone in Romania. It is worth mentioning that Romania is the first country in the world that has developed the exploitation of hydrocarbons associated to saline formations (Jackson & Hudec, 2017c).

By the end of the 18th century, oil exploitation began in the Cămpina region (Romania) on an industrial scale. Romania extracted 275 tons in the year of 1857 only (Vassiliou, 2018). It is worth mentioning that oil extraction in this area dates to the times of the Roman Empire. Likewise, in the year of 1646, oil was already extracted from shallow wells (*Istoria Romaniei*, 1960). In the year 1856 the first oil refinery in the world was built, precisely in the city of Ploiesti, Romania; followed by the largest and most modern oil refinery in Europe, built in the city of Cămpina, also in Romania (Vassiliou, 2018). The fact that Romania was the first country to extract oil is not a coincidence, since probably, Romania possesses one of the largest salt reserves in Europe (Maftai et al., 2009).

It is known that a significant percentage of the world's oil production comes from salt-cored structures, which caused the folding of younger stratigraphic units without intrusion. In addition to oil and gas, most of the world's sulfur, salt and potassium production comes from these types of deposits (Jackson & Hudec, 2017c).

4. HISTORICAL BACKGROUND

In Romania, oil fields are related to the Gura Ocniței – Moreni – Florești – Băicoi – Țintea diapir alignment. These areas have a production history of more than 140 years (Tămaș, 2018) (Figure 3).

The Eastern Carpathian bend zone is an area that has been heavily influenced by salt tectonics. The term salt diapirism was first proposed by the Romanian geologist Ludovic Mrazec (Figure 4) at the third international petroleum conference in 1947 (Tămaș, 2018).

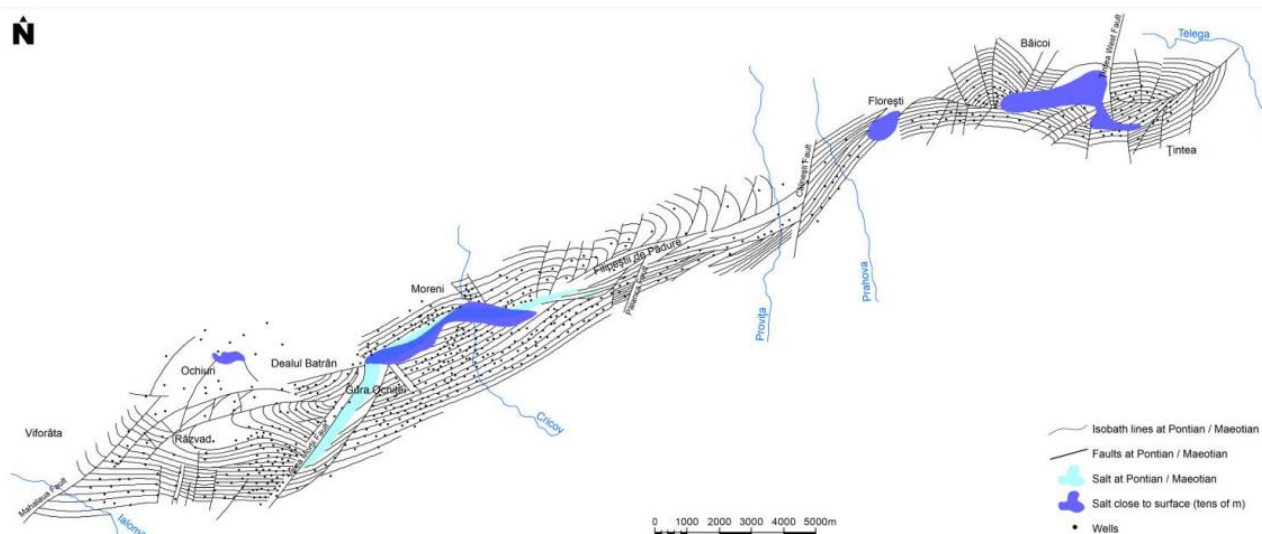


Figure 3. Diapir alignment in Romania. After Tămaş (2018)

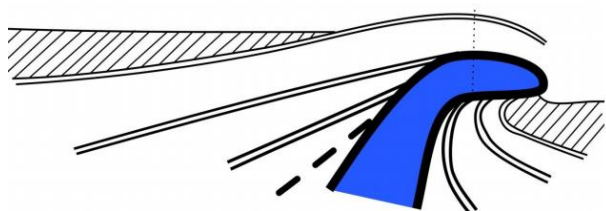


Figure 4. Moren diapir schematics, modified from Mrazec. After Tămaş et al. (2015)

On the other hand, the relationship between salt domes and oil was almost unknown in the United States and Mexico until the discovery of the Spindletop Hill Texas oil field in January 1901 (*How Salt Domes Were Created* | Magna Resources Management Corporation, n.d.). An independent oil prospector and amateur geologist named Patillo Higgins, from Texas, took his Sunday class to a small hill located on level ground and which had a sulfur smell. To amuse his students, Higgins would embed an empty stick in the ground and gas would come out through it, which when ignited caused a flame. This planted the idea in Higgins of the existence of an oil field in the area. After convincing Captain Anthony Francis Lucas, an Austro-Hungarian engineer from modern-day Croatia and naturalized American, both began to drill in the area. On January 10, 1901, after drilling to a depth of 347 m, the well exhaled a gusher more than 50 m high (Figure 5), which aroused great interest in the exploration of similar reservoirs on the Gulf coast (Halbouty, 2002). In Mexico, salt

deposits are known to exist in several regions of the country, such as Chihuahua, Nuevo León and the southeast: Tabasco, Chiapas, Campeche, and Veracruz. However, the salt deposits in the north of the Isthmus of Tehuantepec, located in the southeast of the country, are the most economically important, as well as the best studied. Their discovery dates to the beginning of the 20th century, during the oil exploration works carried out in the Jáltipan-Potrerrillos region, Veracruz, between 1902 and 1906 (Benavides García, 1983).

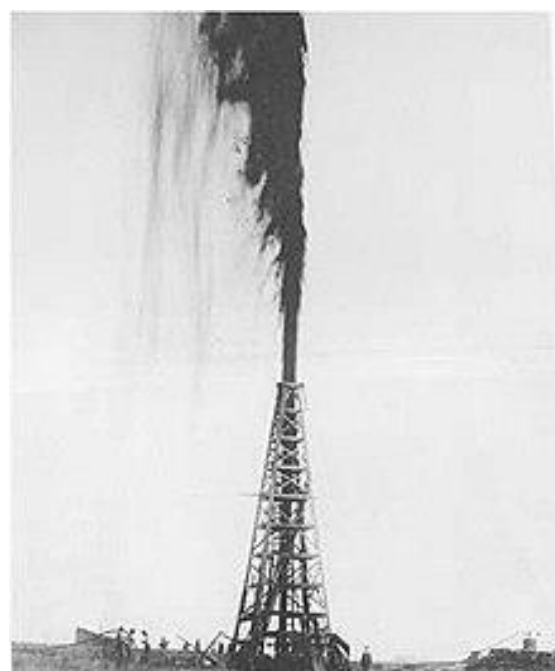


Figure 5. Lucas gusher from in spindletop Texas, 1901, after Wikimedia commons, 2008

5. SALT BASINS IN THE WORLD AND THEIR DEPOSITIONAL ENVIRONMENTS

Large salt diapirs and allochthonous salt layers can only be formed from a thick source layer rich in halite (NaCl). When such source layers do not have a hyperbolic shape, they are known as salt giants, mega evaporites or also as mega halites, due to large extensions such as the Louann salt (Minas Viejas Formation, northern Mexico) from the Jurassic, deposited prior to the opening of the Gulf of Mexico (e.g., Hudec et al., 2013). However, there are no modern analogs to these formations. Currently, the largest salt basin in formation is the Salar de Uyuni (Figure 6), which is located at 3,660 m above sea level in the Bolivian Andes. Despite its large size, this basin does not compare to the size of the

largest ancient evaporite basins that were fed by seawater (Jackson and Hudec, 2017a).



Figure 6. Location of salar de Uyuni located in the andinian region of Bolivia, the white spots in the image above represent an evaporite extension of approximately 10 085 km². Image taken from Google Earth (2020)

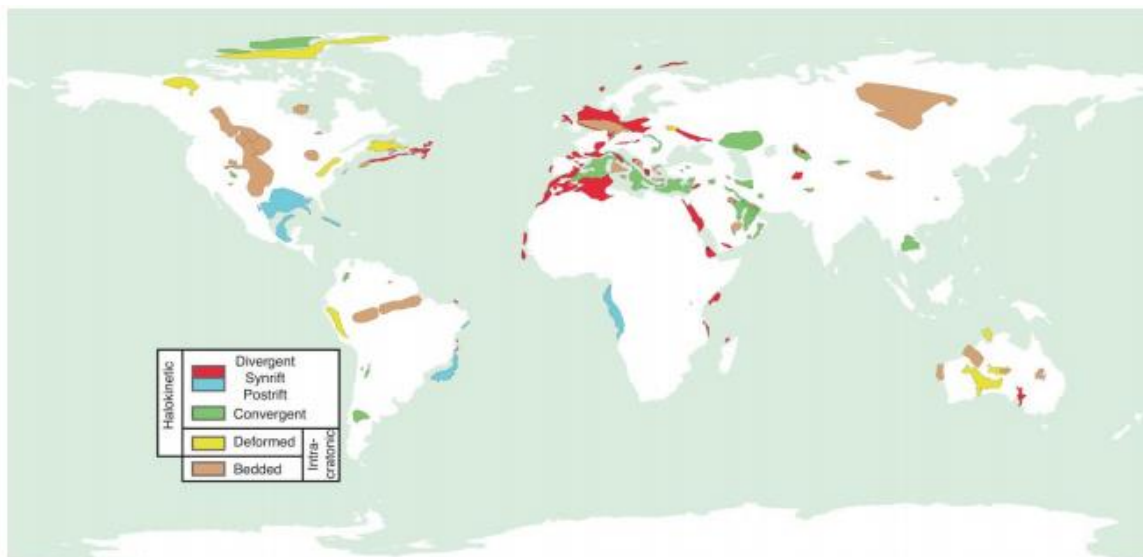


Figure 7. Clasificación de the main evaporite basins (mainly NaCl) Clasificación de cuencas de evaporitas (principalmente de NaCl) located under a context of tectonic environments. After Warren (2010)

These systems were common in regions whose marine water evaporation rate was at its maximum level, such regions were in the past equivalent of today's "horse latitudes" (Figure 8) (J. K. Warren, 2010), also known as high subtropical. Such latitudes are found around 30° north and south of the equator and are characterized by calm winds, low precipitation, and sunny skies (NOAA, n.d.). However, much like present-day evaporites of non-marine origin, the emplacement of Phanerozoic marine evaporites in areas of suitable aridity expanded into the equatorial belts (J. K. Warren, 2010).

The reason for the absence of large salt bodies at present-day time is due to two main reasons, the tectonic setting and the long-lasting paleoclimatic changes known as icehouse-greenhouse-hothouse supercycles (Jackson and Hudec, 2017a). Greenhouse and hothouse conditions favor the precipitation of mega halites, as the warmth makes higher salinity possible, and the seas have only slight fluctuations, which allow a constant salinity level to be maintained under modern-day icehouse conditions. The ice caps cause conditions to be highly variable for a large accumulation of evaporites to take place (Jackson and Hudec, 2017a).



Figure 8. Horse Latitudes, after NOAA, n.d.

The second reason is that the hydrographically isolated conditions required to form evaporites are best developed within large basins when supercontinent breakup or accretion occurs (Jackson and Hudec, 2017a). Continental collisions create hydrographically isolated forearc basins. This is the case of the La

Popa basin in Mexico (Figure 9) and the Muntenian Carpathians in Romania (Figure 10), whereas when a supercontinent breaks apart the rifting process creates hydrologically isolated rifts or shallow ocean basins, for example, in the Gulf of Mexico and the South Atlantic (Jackson & Hudec, 2017a).

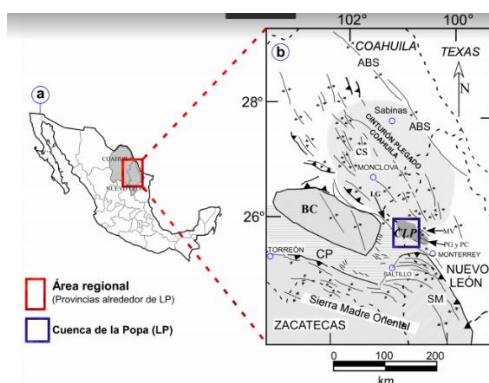


Figure 9. La Popa basin, located between the states of Nuevo León and Coahuila. After Tamez-Ponce et al. (2011)

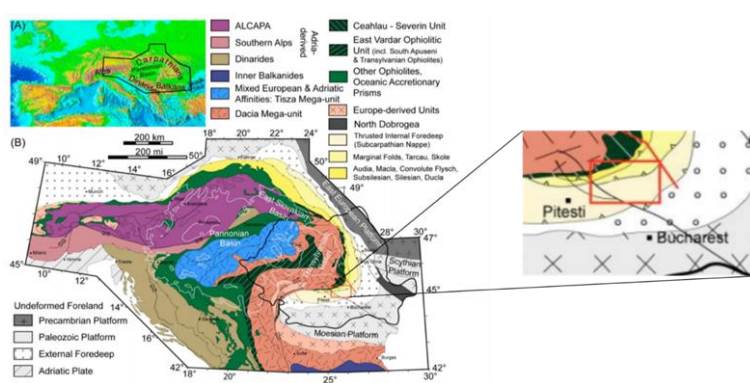


Figure 10. Map of the Alpine, Carpathian and Dinaric mountains. Geological arrangement of the Romanian Carpathians, the red box encloses the study area, the diapir fold zone (DFZ) (modified from Tămaş, 2018)

6. STUDY AREAS

The Carpathian Mountains

As can be seen in Figure 10, the Carpathian Mountains are an eastern extension of the European Alps fold-thrust belt (Krézsek and Bally, 2006). The study area is located 100 km north from Bucharest. The Carpathians Mountains were formed due to the colliding of the African plate against the European plate in an event known as the Alpine orogeny which led to the formation of several basins systems

on top of the Eo-alpine structures (Krézsek and Bally, 2006).

The first colliding took place during the late Jurassic, as consequence nappe systems were created during the middle cretacic, (Frisch et al., 2010), the strong bending on the area is characteristic of the Carpathians and there are two main salt horizons (Figure 11), both dating to the Miocene, the early Burdigalian and the Middle Serravallian. The evaporites were first deposited on the Carpathians foreland and later over the nappes. The salt formation studied on this paper is of Burdigalian age.

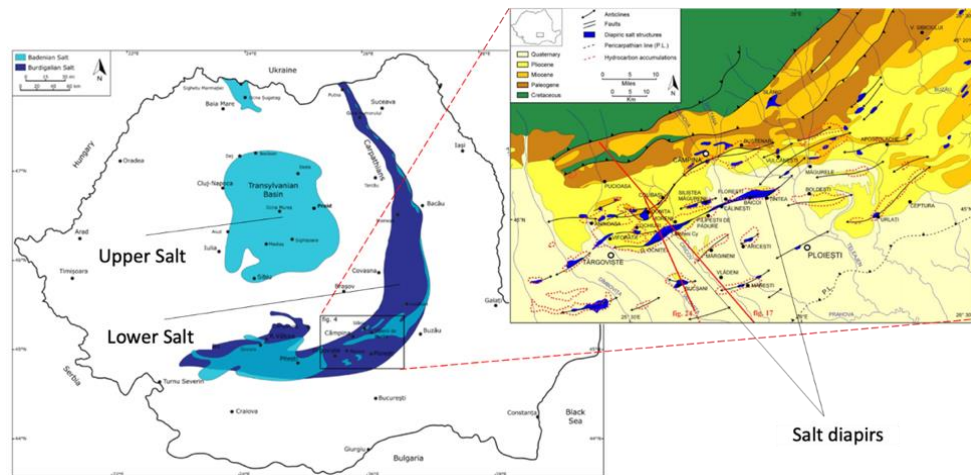


Figure 11. Map of the lower and upper salt formations, on the zoomed area the salt diapirs present on the area can be. Modified from Tămaş (2018)

The late deformation phase of the region is related to compression within the plate accommodated by thick-skinned deformation, (Wallachian phase), (Hippolyte and Sandulescu, 1996). The Diapirs Fold Zone (DFZ) sedimentary column comprises over 4 km thick Cretaceous to

Middle Miocene clastic deposits overlying a thin succession of Middle Miocene evaporites and shales. The Cretaceous to Middle Miocene section has been locally covered by more than 2 km of Late Miocene to Quaternary shallow marine and fluvial sediments (Figure 12 and Table 1) (Tămaş, 2018).

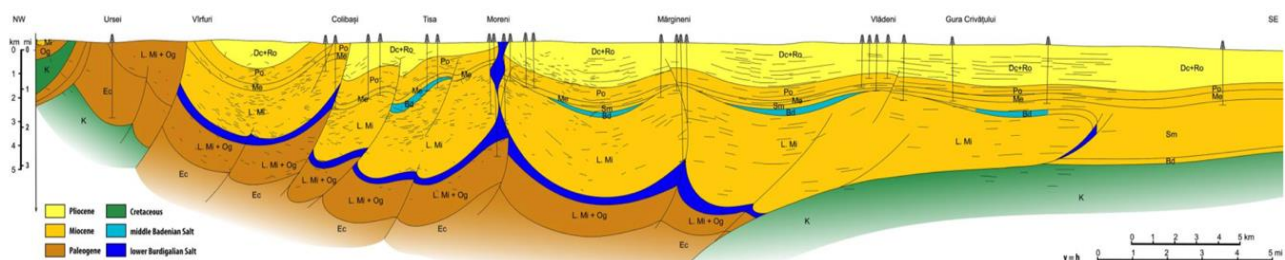


Figure 12. NW-SE simplified geological section through the Moreni diapir, where the local stratigraphy is shown, K=Cretaceous, Ec= Eocene, Oc=Oligocene, L.Mi=Early Miocene, Bd=Badenian, Sm-Sarmatian, Me=Maeocene, Po=Pontianian, Dc=Dacian, Ro=Romanian. Taken from Tămaş (2018)

“La Popa” Basin

The other study area encompassed in this study is “La Popa” a foreland pull apart type basin located in the northern part of Mexico, 85 km away the city of Monterrey, this basin is located over the front part of the eastern *Sierra Madre* (ESM) in that basin there are gypsum deposits representing eroded salt reserves, a 25 km fault- shape structure can be identified in blue on the image below, indeed, that structure is a salt weld (Figure 13).

La Popa basin is Linked to the opening of the Gulf of Mexico (200 Ma) with Callovian salt (163 Ma) (Minas Viejas/Sal Louann Formation). The formation of the basin can be described in 4 phases, Figure (14):

- Opening of the Gulf of Mexico, displacement of the Yucatan block, deposition of Callovian salt.
- End of salt deposition.
- Creation of oceanic floor during the Tithonian.
- Actual disposition of the Gulf of Mexico.

The salt tectonics in “La Popa” basin have been influenced by the formation of WSM formation during the late Cretaceous up the early Paleogene (70-50 Ma). The salt of Callovian age is called the “*minas Viejas*” formation in Mexican literature and Louann salt in American literature, is overlaid by a late Cretaceous to Middle Eocene siliciclastic succession deposited during the uprising of the WSM (70 Ma-45 Ma) and the Zuloaga formation of marine limestones of middle Jurassic to late

cretaceous age (Figure 15 and Table 1), which covers the surface, (Lawton et al., 2001). The initial thickness of the salt is estimated in 2,100 m of halite, followed by 520 m of carbonate black limestone and halite intercalation and a basal interval of carbonate black limestone of 370 m, (Lopez-Ramos, 1982).

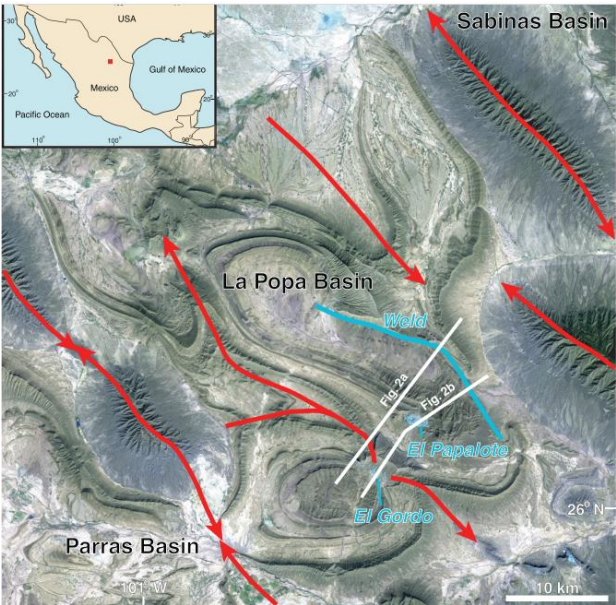


Figure 13 The “El Gordo” and “El Papalote” diapirs and “La Popa” salt weld of 25 km of extensions (blue). Axial traces of detachment folds of the Mexican orogeny (red). After Rowan et al. (2003)

Table 1. Comparison between the stratigraphy of both basins the Carpathians (right) and La Popa (left). In red the evaporite formations are shown and in blue the same ages in both basins, the salt in La Popa basin its older than the salt in the Carpathians. Modified from Vega and Lawton (2011)

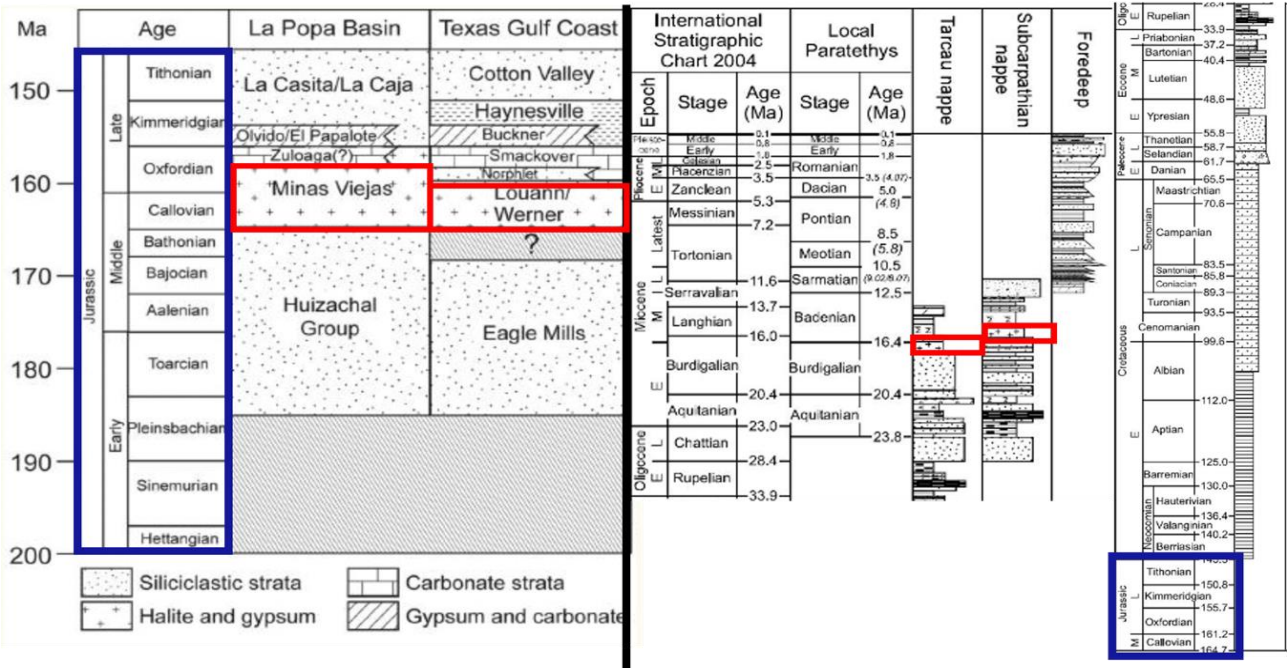


Figure 14 Paleogeographic reconstruction of the Gulf of Mexico, a) beginning of the opening of the Gulf with the displacement of the Yucatan block and therefore, the beginning of Callovian salt deposition; b) end of salt deposition; c) creation of the ocean floor during the Tithonian; d) Actual disposition of the Gulf of Mexico. After Roelofse et al. (2020)

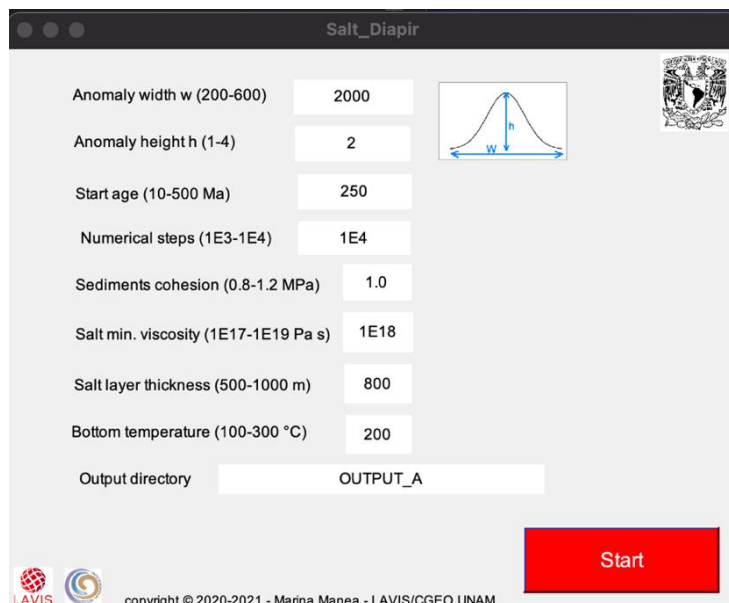


Figure 15. Interface of the Salt_diapir v 1.0 with the parameters displayed

7. METHOD AND RESULTS

Since salt diapirs represent an important part of the world's hydrocarbon reserves it is of great importance to understand the evolution of salt basins and diapirs, as well as their causes and occurrence. For this, it is necessary to carry out studies where the evolution of different basins is compared. Numerical tools were used to study the evolution of salt diapirs under different conditions.

To simulate the evolution of the salt diapirs the software Salt_Diapir v1.0 created at the national laboratory of advanced scientific visualization of the National Autonomous University of Mexico (LAVIS UNAM, by its initials in Spanish) was used.

The software performs numerical simulations under the following considerations: Linear temperature distribution along with the depth, typical rheological behavior of halite, no tectonical deformation is considered in the simulations, an initial salt anomaly in the form of a Gaussian bell (From now on referred to as Gaussian anomaly), density difference between the salt layer (salt=2.1 g/cm³) and sediments (sediments=2.7 g/cm³). Interface of the software is show in the image below (figure 16).

a) Anomaly width w = indicates the horizontal extent of the Gaussian anomaly,

b) Anomaly height = indicates the vertical extent of the Gaussian anomaly,

c) Start age = indicates the time it takes for the diapir to surface,

d) Numerical steps = indicates the number of iterations the program performs to simulate the diapir,

e) Sediments cohesion = indicates the cohesion of the sediments overlying the salt layer,

f) Salt min. Viscosity = indicates the viscosity of the salt layer,

g) Salt layer thickness = indicates the thickness of the salt layer,

h) Bottom temperature = indicates the temperature of the salt layer.

To better understand how the rising of salt diapirs is affected by different parameters, 26 simulations of salt diapirs were performed on the software Salt_Diapir v1.0. The aim of these simulations was to observe how the parameters (viscosity, temperature, salt layer thickness and dimensions of the gaussian anomaly) affect the time that takes a salt diapir to reach the surface. The simulations 1 to 9 show the modifications over the dimensions (height and width) of the gaussian anomaly and the effects that this parameter has on the evolution of the salt diapir (salt layer thickness, temperature and viscosity were kept constant). Simulations 10-13 show the effects of the

temperature and its effects on the evolution of salt diapirs. For these simulations the salt layer thickness, viscosity and the dimensions height and width of the gaussian anomaly were kept constant. Simulations 14-18 depict the modifications on the salt layer thickness and its influence on the evolution and rising on the salt diapir. For these

simulations the viscosity, temperature, and dimensions of the gaussian anomaly were kept constant. For the simulations 19-26, the viscosity of the salt layer is modified in a range between 1×10^{17} to 1×10^{19} Pa s, while the temperature, salt layer thickness and gaussian anomaly dimensions were kept constant (figure 16 and table 2).

Table 2. Simulation conditions

Simulation number	Salt. Min viscosity [Pa s]	Bottom temperature [°C]	Start age [Ma] (time it takes for the diapir to reach the surface)	Salt layer thickness [m]	width [km]	height [km]	h/w
1	1.00E+18	200	610	800	2	2	1
2	1.00E+18	200	293	800	2	5	2.5
3	1.00E+18	200	116	800	2	10	5
4	1.00E+18	200	380	800	1	2	2
5	1.00E+18	200	139	800	1	5	5
6	1.00E+18	200	22	800	1	10	10
7	1.00E+18	200	257	800	0.5	2	4
8	1.00E+18	200	37	800	0.5	5	10
9	1.00E+18	200	4	800	0.5	10	20
10	1.00E+18	150	140	800	1000	5	-
11	1.00E+18	175	137	800	1000	5	-
12	1.00E+18	225	139	800	1000	5	-
13	1.00E+18	250	138	800	1000	5	-
14	1.00E+18	200	826	500	1000	5	-
15	1.00E+18	200	750	600	1000	5	-
16	1.00E+18	200	180	700	1000	5	-
17	1.00E+18	200	136	900	1000	5	-
18	1.00E+18	200	129	1000	1000	5	-
19	1.00E+17	200	129	800	1000	5	-
20	2.50E+17	200	132	800	1000	5	-
21	5.00E+17	200	136	800	1000	5	-
22	7.50E+17	200	136	800	1000	5	-
23	2.50E+18	200	142	800	1000	5	-
24	5.00E+18	200	151	800	1000	5	-
25	7.50E+18	200	159	800	1000	5	-
26	1.00E+19	200	165	800	1000	5	-

Graph 1 (in figure 16) shows the relationship between time and ascension of the diapir when viscosity of the salt layer and the rest of the parameters are kept constant. As can be seen, the higher the viscosity is, the longer the ascension time. The upward trend line and the equation of the straight line obtained can also be observed, the equation establishes diapir's ascension time as a function of salt viscosity l to $T = 3 \times 10^{-18x} + 132.28$ where T is the ascension time and x is the viscosity of the salt layer.

Graph 2 (in figure 16) shows the relationship between the thickness of the salt layer versus the time it takes to the diapir to reach the surface, and the rest of the parameters are kept constant, it is observed that the thicker the salt layer is, the shorter the ascension time. It can also be concluded that the behavior of the function is different when the salt layer thickness is smaller than 600 m, therefore, two equations were obtained, one for a thickness smaller than 600 m (blue) and another for a thickness bigger than 600 m (orange). Therefore, for a thickness

bigger than 600 m: $T = -0.76x + 1206$ where T is the ascension time and x is the salt layer thickness. For a thickness bigger than 600 m we have the following equation $T = -0.1771x + 301.86$ where T is the diapir ascent time and x is the thickness of the salt layer.

Graph 3 (in figure 16) shows the relationship between diapir's bottom temperature versus ascension time, with all other parameters kept constant, unlike the other parameters, the relationship between temperature and time is not proportional and, after the Salt_Diapir v 1.0 software, temperature does not

play a very important role in the diapir's ascension to the surface.

Graph 4 (in figure 16) shows that while the anomaly height (h), at constant parameters, is bigger than its width (w), the ascent time also decreases, this is very clearly observed in model M9, where the formation time is only 4 Ma. An exponential equation was also obtained, this equation establishes that $T = 575.33e^{-0.266x}$ where T is the ascent time and x is the height over width ratio of the anomaly.

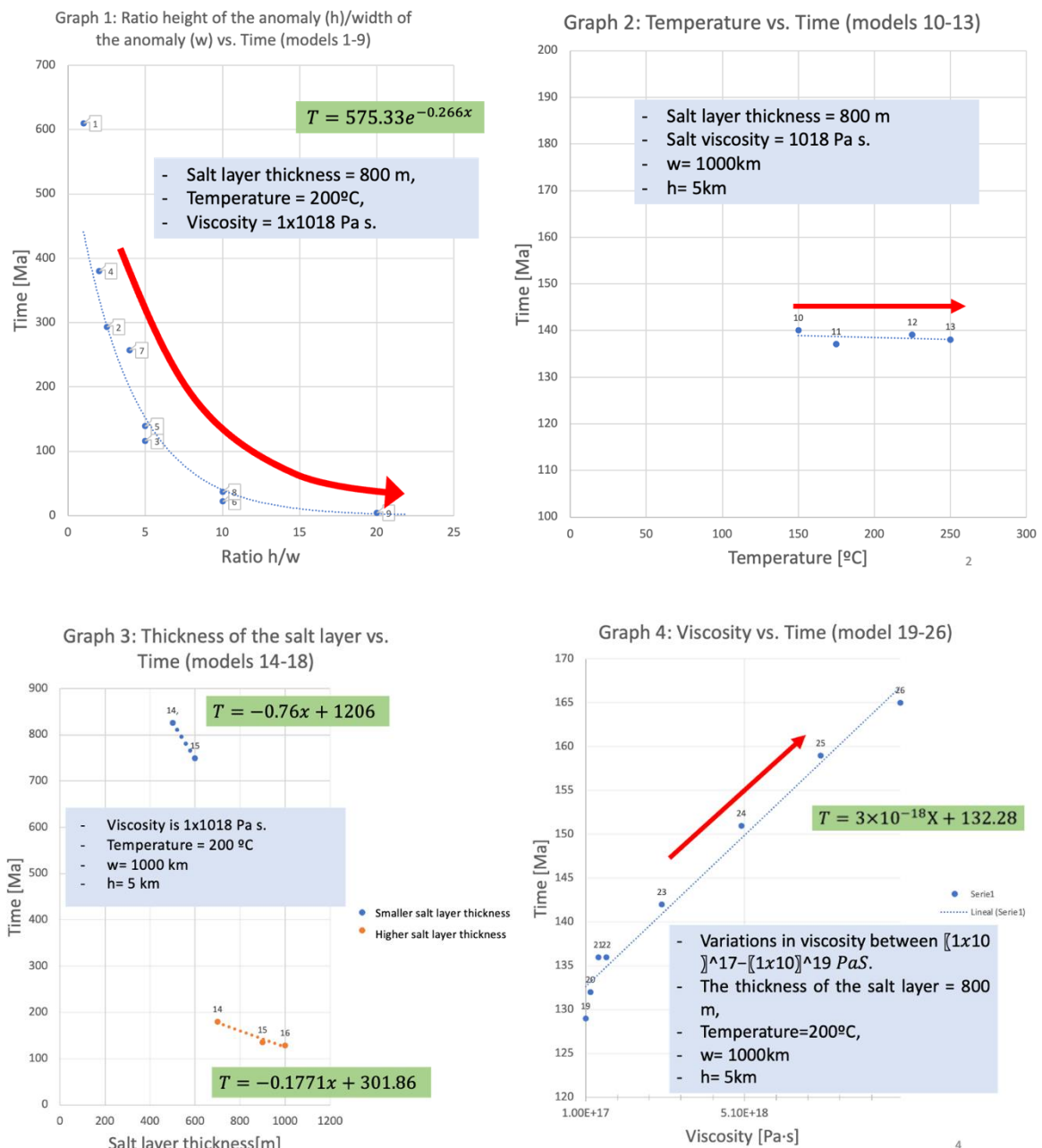


Figure 16. Simulation results. The number above the dots on the graphs indicates the model number. Parameters are Viscosity [Pa s], temperature [°C], salt layer thickness [m], time [Ma], Gaussian anomaly base width (w) [km] and Gaussian anomaly height (h) [km].

8. REGIONAL DIFERENCE AND FUTURE DIRECTIONS

According to the geological history of both basins, the processes that took place are similar, both are foreland basins and were affected by compressional tectonic events, such as the Alpine orogeny and the Mexican orogeny, which gave origin to the Carpathian Mountains and the eastern Sierra Madre respectively. From the above it can be deduced that the diapirs present in both basins have been affected by tectonic shortening.

Both in the La Popa and Carpathians sedimentary environments there were periods of passive diapirism, due to sediment deposition on the salt (“downbuilding”), as well as active diapirism due to compressional shortening events that affected it. The main difference between both basins lies on the salt’s age of deposition; the salt present in the La Popa Basin dates to the Jurassic, more specifically to the Bajocian-Bathonian age (Pindell et al., 2021), whereas the salt in the Carpathians is much more younger since there are Miocene salt formations, specifically from Burdigalian and Serravallian ages (Tămaş, 2018). Likewise, the salt layer thickness is thicker in the La Popa basin than it is in the Carpathians. The thickness of the La Popa salt layer is greater than 2 km (Vega and Lawton, 2011) whilst the salt layer thickness in the Carpathians its approximately 1.5 km (Tămaş, 2018).

On the simulations carried out with the Salt_Diapir v 1.0 software (Figures 17 and 18), it can be observed that the horizontal extension of the Carpathians diapir its smaller than the one in the La Popa basin diapir. This is due to the difference

between the thickness of the salt in both basins. Likewise in both basins a detachment is observed. It is also evident that the salt weld is narrower in the Carpathians, which indicates the importance of the salt thickness in the development of the diapir. Another aspect of the rising of a salt diapir is the importance that the age of salt deposition and the compressional shortening play on the rising of a salt diapir. Despite that the salt of Miocene age in the Carpathians is younger than the Jurassic salt in the La Popa basin, both have reach to the surface, even doe the process of salt ascension piercing through the overburden takes millions of years. Whereas the rising of salt diapirs in the La Popa occurs by downbuilding processes, in the Carpathians the rising of the diapirs is “helped” by the compressional tectonic shortening of the Carpathians and acting like an extruder of the salt.

To study, the evolution and differences between the La Popa basin and the eastern Carpathian bend zone in a deeper way it is necessary to know the conditions present in both basins, e.g. the arrangement and disposition of diapirs and salt formations in each one of the basins. In addition, since the program used in this research only considers density differences during diapir development, in future works downbuilding and tectonic shortening processes should also be considered. This could help to represent the deformation processes, evolution and final configuration of salt diapirs and salt basins on a more reliable way. Differences in salt temperature should also be considered since the temperature distribution is not uniform and it directly affects salt’s density and buoyancy, which in turn affects salt flow velocity, (Jackson and Hudec, 2017c).

La Popa

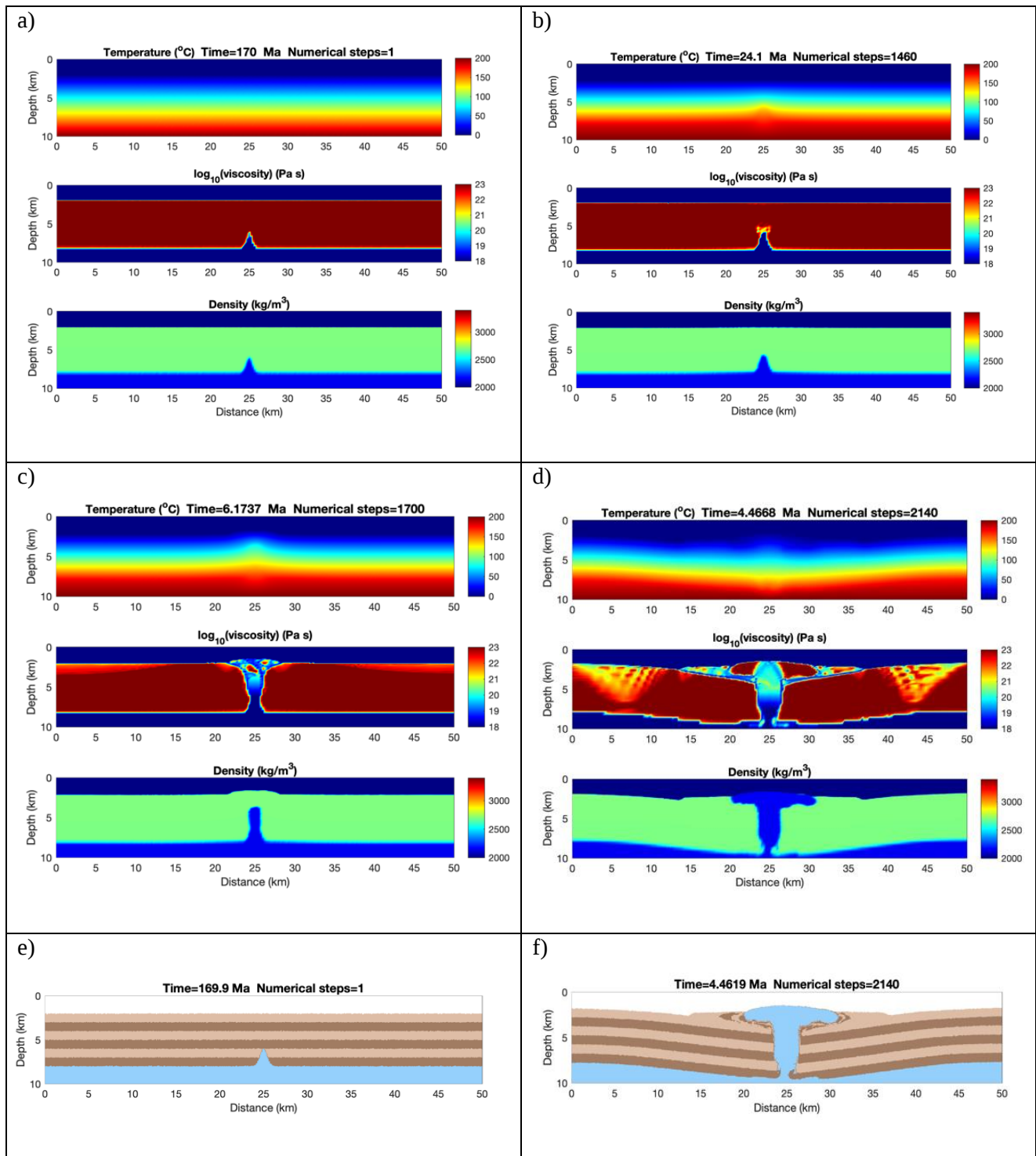


Figure 17. Models of La Popa basin made with the salt diapir software, a) initial temperature distribution in the La Popa basin, d) final temperature distribution in the La Popa basin, e) original arrangement of the strata in La Popa, f) final disposition of the strata in La Popa caused by diapirism.

Carpathians

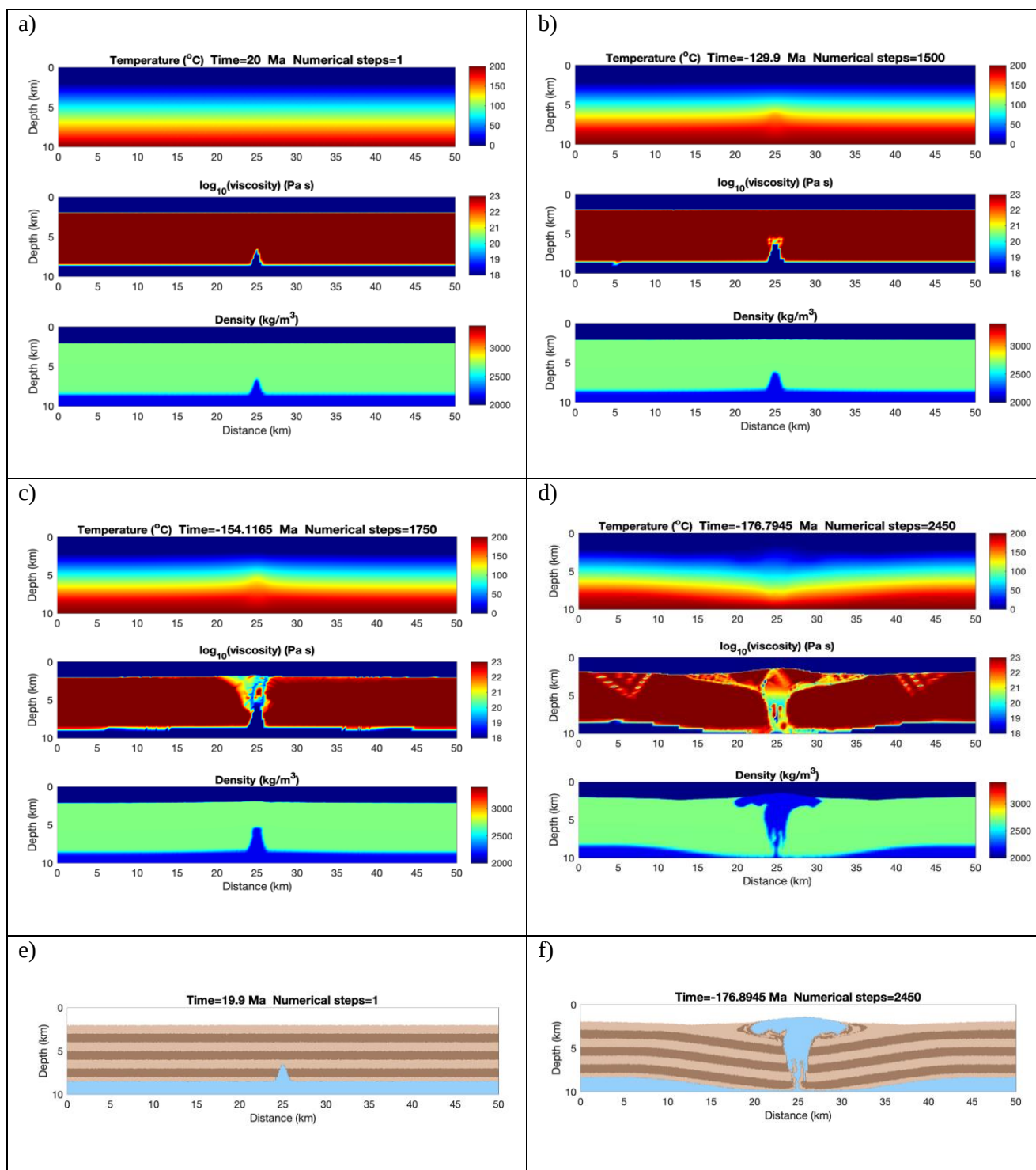


Figure 18. Models of the Carpathians basin made with the salt diapir software, a) initial temperature distribution in the Carpathian, d) final temperature distribution in the Carpathian, e) original arrangement of the strata in the Carpathian, f) final arrangement of the strata in the Carpathians caused by diapirism.

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