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Present-day overpressure in southern Tunisia: Characterization, possible causes and implications for drilling operations

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ABSTRACT

Formation pore pressure in sedimentary basins is known to vary with depth. These variations are caused by one or more sedimentary, tectonic or diagenetic mechanisms. In Mesozoic basins of southern Tunisia, a detailed study has been carried out in order to characterize the regional pore pressure profile. The results show an over-pressure interval ranging from upper Triassic to lower Jurassic salts series.

The study of possible overpressure mechanisms allows us to conclude that the present-day overpressure can be explained by the active compressional tectonics that is affecting the North African margin. Nevertheless, other past overpressures have been interpreted from this study and have been attributed to different mechanisms. One of the most important paleo-overpressure mechanisms was gypsum dehydration. This diagenetic reaction has led to pore pressure approaching lithostatic pressure, demonstrated by hydraulic fractures and beef veins observed in fields.

In this study, we established a method based on a depth chart diagram enabling the identification of the likely mechanism involved in reservoir overpressure build-up and/or the prediction of a potential mechanism. This result could be important in the analysis of unexplored basins to predict the anticipated pressure profile and thereby reduce the risk of encountering unexpected overpressured zones and related drilling hazards. This method could be applied to other sedimentary basins with standard geological backgrounds.

1. Introduction

In sedimentary basins, fluids in rocks' porosity indicate a pressure distribution profile that is not always normal (hydrostatic pressure) (Hunt, 1990; Bigelow, 1994a,b; Cobbold and Mourgues, 2004; Cobbold et al., 2009; Radwan et al., 2020). In fact, in oil exploration wells, we had often recorded abnormal changes to this hydrostatic pressure profile leading to pore pressure anomalies. These anomalies are called abnormal high or overpressure (above the hydrostatic) or under pressure (below the hydrostatic). Overpressure has been commonly detected around the world. This abnormal pore pressure is needed in oilfields exploration and production (Fertl et al., 1994; Xie et al., 2001; Akrou et al., 2016; Radwan and Sen, 2020; Agbasi et al., 2021).

The overpressure in reservoirs is a valuable parameter that helps economise the production energy. However, the same parameter forms a potential source of danger that may cause human casualties and heavy

damage to the equipment and environment while drilling. It can be noted that all serious historical accidents are related to overpressurised fluids, and the latest example was the Gulf of Mexico blowout recorded in April 2010. Overpressure has been described in many sedimentary basins worldwide (Hunt, 1990; Bigelow, 1994a,b; Bjørlykke, 1994, 1998, 1998; Swarbrick and Osborne, 1998; Mourgues and Cobbold, 2003; Van Ruth et al., 2003; Akrou et al., 2012, 2016, 2016; Sen et al., 2019). Several former works have studied these abnormal pore pressure mechanisms (Smith, 1971; Fertl, 1976; Magara, 1978; Osborne and Swarbrick, 1997). These studies assume that a compaction disequilibrium, fluid's volume expansion (during hydrocarbon generation or from mineral transformations) and tectonic stress are the major contributors to a great overpressure buildup (Shi and Wang, 1986; Spencer, 1987; Bethke, 1988; Luo and Vasseur, 1992; Audet, 1995; Gordon and Flemings, 1998; Swarbrick and Osborne, 1998; Law and Spencer, 1998; Zhao et al., 2018; Tremosa et al., 2020).

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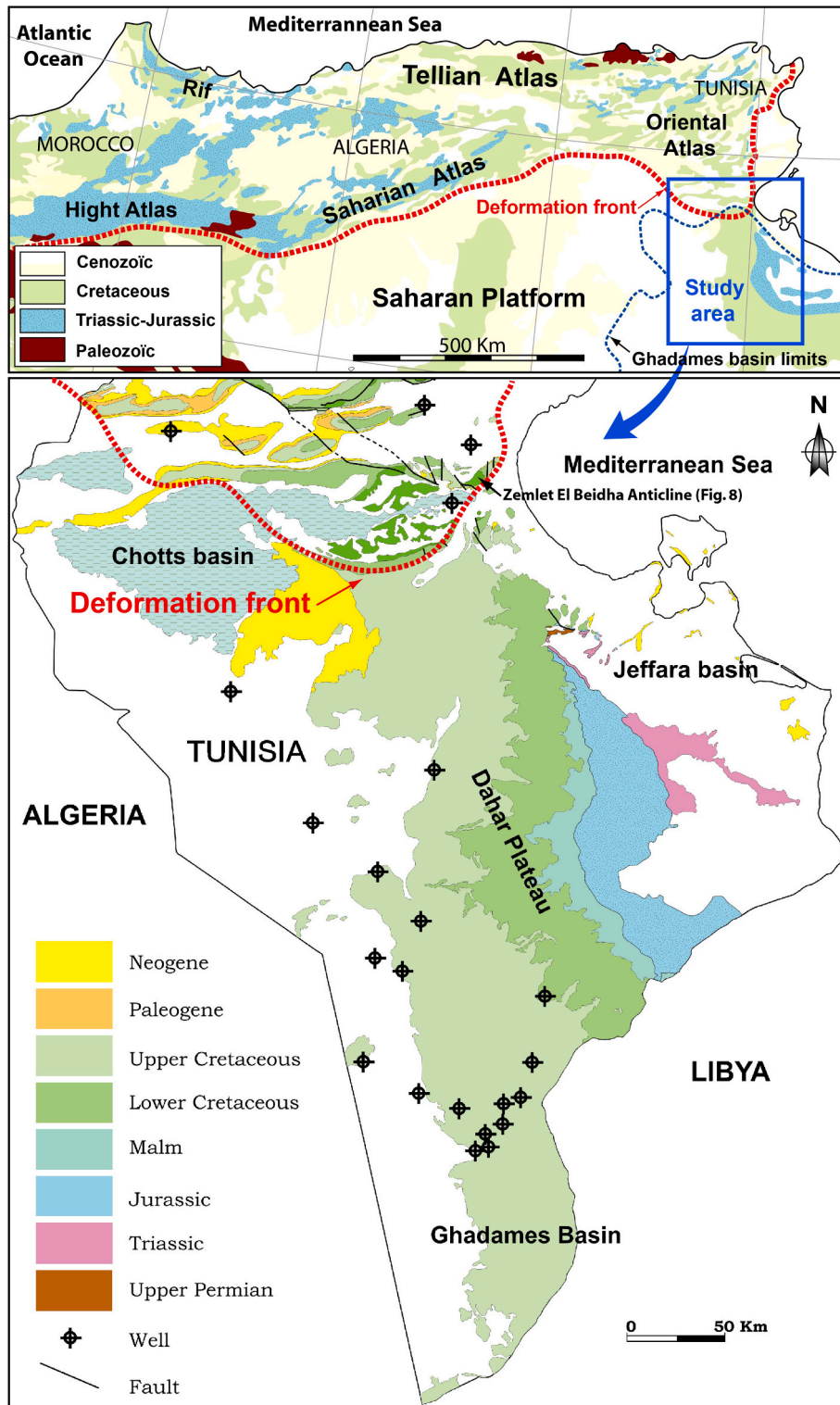


Fig. 1. Location map of the studied area. Southern Tunisia contains folded Atlasic domains to the north and a flat platform to the south. The southernmost part belongs to the Ghadames basin, which is rich in hydrocarbons.

In this work, we first characterised the pore pressure profile in southern Tunisia and then explored the possible mechanisms involved in the pressure distribution.

This study aimed to deepen the understanding of the overpressure phenomenon creation and evolution and may further contribute to petroleum exploration in southern Tunisia or similar foreland basins. To this end, we relied on drilling data and geological field data. The study

area belongs to the most explored North African oilfields that produce more than 3 MBOD (Million Barrel Oil a Day). This high hydrocarbon potential should allow a good characterisation of the pore pressure profile and help us find crucial links between oil exploration and fluids' overpressure.

| | Age | Formation | Log | Thickness | Potential | Tectonics |
|------------|---------------|--------------------------|-----|-------------|----------------|-----------|
| | CENOZOIC | | | | | |
| | | Sand dunes | | 0 - 200 m | Atlasic unc. | |
| CRETACEOUS | SENONIAN | Abiod | | 100 - 150 m | | |
| | | Aleg | | 450 m | | |
| | TURONIAN | Zebbag | | 250 - 300 m | | |
| | CENOMANIAN | | | | | |
| | ALBIAN | Albian SST | | 50 m | | |
| | APTIAN | Orbata | | 50 m | | |
| | BARREMIAN | Continental Intercalaire | | 350 m | | |
| | NEOCOMIAN | | | | Sidi Khalif | |
| JURASSIC | MALM | Sebaia | | 400 m | | |
| | DOGGER | Abreghs | | 350 m | | |
| | LIASSIC | Adjaj | | 450 m | | |
| TRIASS. | TRIASSIC | Trias Carbonate | | 50 m | | |
| | | TAGI - Kirchaou | | 100 - 150 m | Hercynian unc. | |
| PALEOZOIC | CARBONIFEROUS | M'Rar | | 0 - 1200 m | | |
| | DEVONIAN | Tahara | | 0 - 80 m | | |
| | | Aouinet Ouenine | | 0 - 500 m | | |
| | | Ouan Kasa | | 0 - 200 m | | |
| | | Tadarart | | 0 - 250 m | Taconic unc. | |
| | SILURIAN | Acacus | | 250 - 700 m | | |
| | | Tannezuft | | 550 m | | |
| | ORDOVICIAN | Bir Ben Tarta | | 400 m | | |
| | | Kasbah Leguine | | | | |
| | | Sanrhar | | | | |

Fig. 2. Lithostratigraphic column of southern Tunisia sedimentary basin (North of Ghadames Basin).

2. Geological setting and stratigraphy

The North African margin is characterised by thick Mesozoic sedimentary basins. The sedimentary cover overlays all the Paleozoic Formations within a major unconformity. The Paleozoic series recorded complex tectonic history starting from Pana-African, through the Caledonian and ending up with the Hercynian orogeny. The latest major unconformity occurred during the early Cenozoic and caused this time after the African tectonic plate collision with the Eurasian plate. Therefore, the North African Tertiary sediments were mainly of a terrestrial type, were derived from fold ranges erosion (Fig. 1).

Normal fault controls these sediments and are contemporaneous to the abandoned rifting stage (Busson, 1967; Van de Weerd and Ware, 1994; Rudkiewicz et al., 1997; Echikh, 1998; MacGregor et al., 1998; Klett, 2000). Sedimentary formations started with the deposition of continental Early and Middle Triassic Sandstone Unit called the TAGI Formation that forms the main hydrocarbon reservoir target in this region (Acheche et al., 2001; Gabtni et al., 2006; Underdown and Redfern, 2007). Thick evaporite masses overlay Triassic sands (Upper

Triassic-Liassic). The evaporites are contemporaneous with active subsidence deposited in a shallow and confined sea environment (Ben Ismail and M'Rabet, 1990; Ciarapica and Passeri, 1980; Lugli, 2001; Kamoun et al., 1999; Kamoun et al., 2001). Then the Dogger and Malm Formations are made of thick intercalations of shale and carbonates deposited in a shallow confined to open sea shelf environment (Kamoun et al., 1999; Acheche et al., 2001). The Cretaceous formations begin with terrestrial fluvial sandstone bodies called the Continental Intercalaire Formation. This formation is explored for its huge water reserves in the Saharan domains (Hamed et al., 2013; Besser et al., 2018; Besser and Hamed, 2019). Then marine carbonate shelf formations overlay the lower Cretaceous sands and shale within two important transgressive stands: Aptian then Turonian. The Turonian high stand carbonates match with a maximum flooding surface. Then, the general sea level decrease began and led to Senonian outer shelf to shoreface facies. The Senonian consists of carbonates, marls, mudstones and locally thick evaporite sequences. This formation forms the last marine sedimentations in the Saharan Platform and is capped by Mio-Pliocene continental Sands in a major unconformity (Fig. 2).

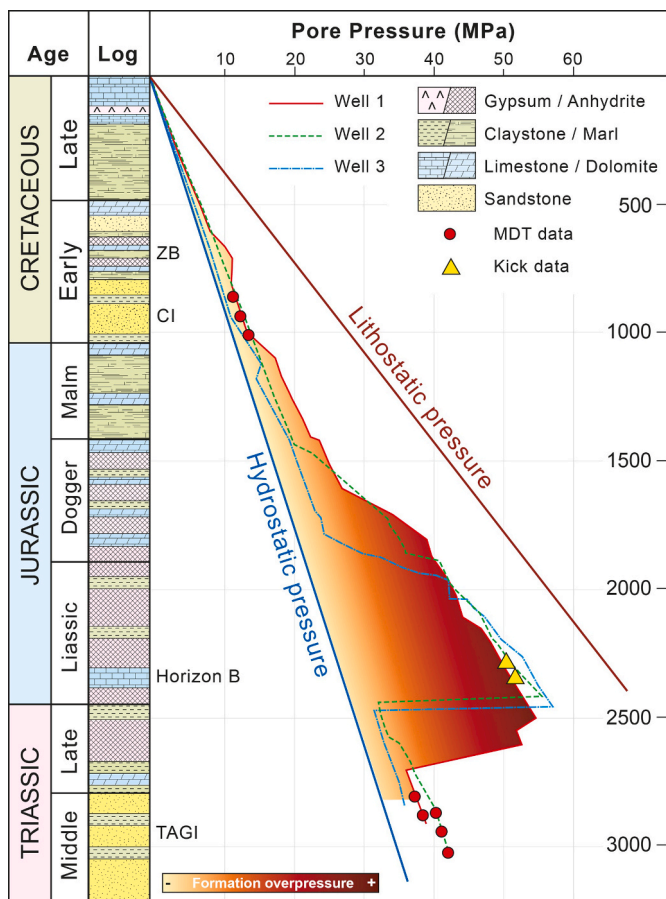


Fig. 3. Pore pressure profile in southern Tunisian basins. This pressure profile shows overpressure interval ranging from middle Jurassic and late Triassic. This overpressure is present in all studied wells shown in Fig. 1. BH: Bouhedma Formation observed in Zemlet El Beidha outcrops sites (Figs. 9 and 10), CI: Continental Intercalaire Formation. Horizon B: 20 m thick Oolitic limestone marker inside Liassic evaporite series, locally water-bearing and helped to calculate real formation pressure by water influx (kick data). TAGI (Trias Argilo-Gresieux Inferieur) reservoir formation. MDT: Formation pressure surveys took in the Continental Intercalaire and TAGI formations.

3. Materials and methods

In our study, the pore pressure was estimated using drilling fluid data. These data were locally supported by direct pressure measures from reservoir wellbore (MDT: Modular Dynamic Test) and well test

(DST: Drill Stem Test). Hanor and Sassen (1990) successfully applied the mud weights method in the Gulf Coast basin. The quality controls of this method were achieved by surveying gases in mud while drilling (Mouchet and Mitchell, 1989; Zhang, 2011). However, mud weights represent an upper limit on formation pressure because the mud column weight in the borehole has to be a little greater than the formation pressure (Bauuche et al., 2020). This avoids the possibility of taking a fluid influx from the formation (Lee and Deming, 2002a,b) and keeps mechanical support of the wellbore in shale. However, in porous and permeable formations, overbalanced mud weight leads to slow rate mud losses into the formation called seepage, useful for the creation of the mud cake.

In our case study, the Ghadames basin mud weights were optimised throughout the large number of development oil wells drilled all over this region (many thousands). The ideal mud weight was based on many historical borehole stability problems (caving, pipe stack, collapsing and fluids flowing). Therefore, we can consider that, in our case, the used mud weights closely describe the formation pressure trends.

4. Results

4.1. Pore pressure profile in southern Tunisia

The formation pressure profile versus depth was estimated from the mud weight data (Fig. 3). The distribution shows an important overpressure located in the late Triassic-middle Jurassic interval in all oil wells of the studied region. Formation pressure in this zone is close to the lithostatic pressure between the Pliansbachian (Liassic) to Norian (Upper Triassic) age. This interval consists of evaporite sequences (anhydrite, halite, claystone and minor dolomitic limestone) ranging from 1500 to 2500 m in the studied area.

Above and below this overpressure interval a normal formation pore pressure was noted reflected by mud weights close to the hydrostatic gradient. Formation pore pressure surveys confirm these normal pressures (MDT) recorded in different reservoirs: Early Cretaceous (Continental Intercalaire water-bearing), Triassic (TAGI formation), Silurian (Acacus formation) and Ordovician (El Hammra formation).

4.2. Overpressure origins in southern Tunisia

In southern Tunisia, the overpressure interval remains in the same stratigraphic level (upper Triassic-middle Liassic). However, this overpressure was still almost constant in extent and space along a huge area as big as the Ghadames basin itself. This interval is made of massive anhydrite and salt beds intercalated with thin shale beds. Considering the studied region diagenesis and tectonic history, we explored the possible causes of the present-day overpressure in southern Tunisia in the subsequent sections.

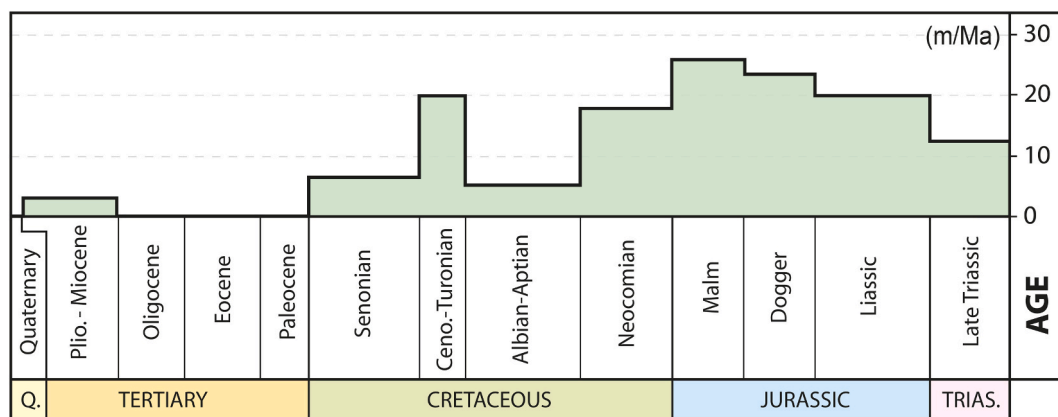


Fig. 4. Sedimentary rate history of southern Tunisian formations since the Late Triassic.

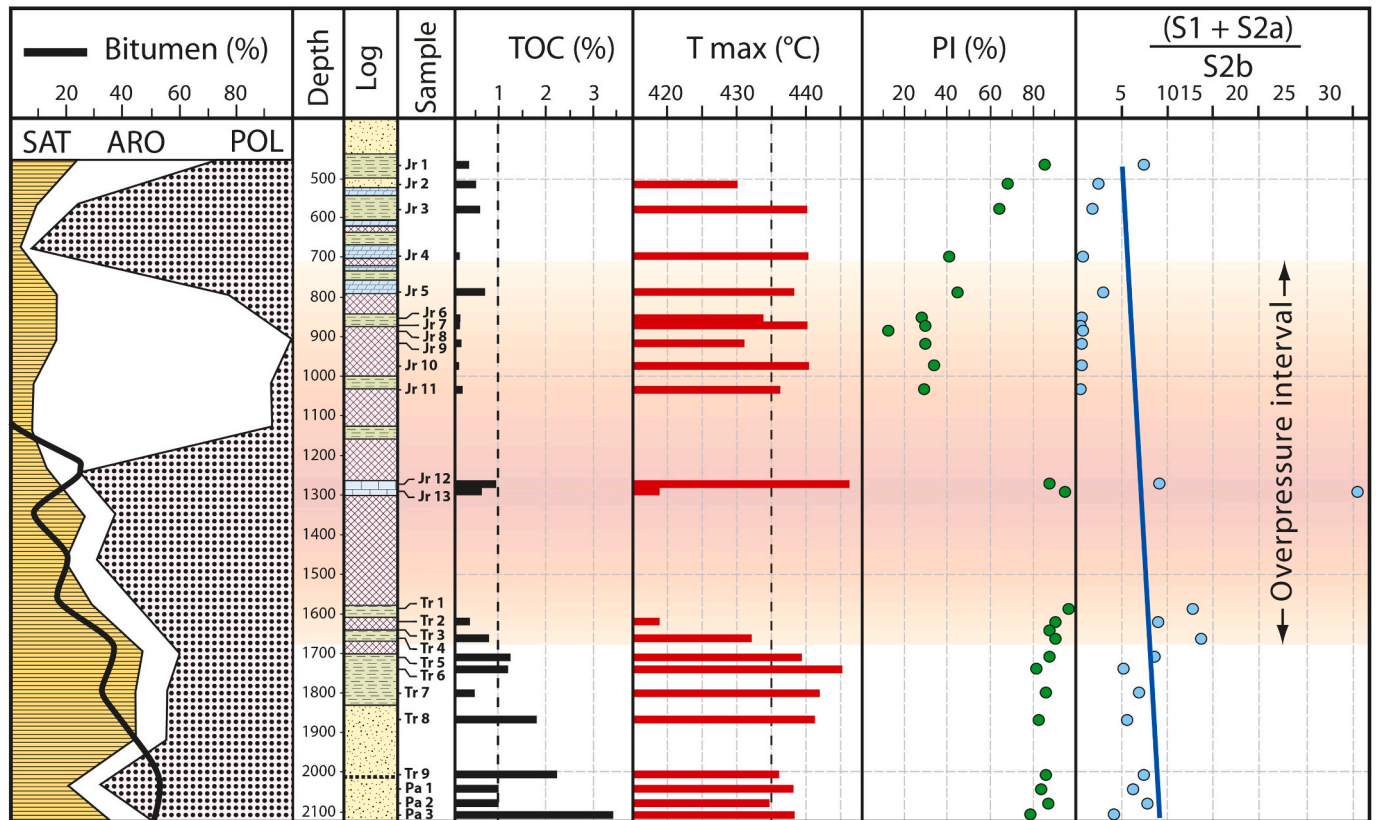


Fig. 5. Geochemical analysis samples from well-1. Jr: Jurassic samples; Tr: Triassic samples; Pa: Paleozoic samples; SAT, ARO and POL= Saturated, Aromatic, and Polar hydrocarbons; TOC = Total Organic Carbon; Tmax = the temperature at the top of the S2b peak; PI= Production Index $(S1+S2a)/(S1+S2a + S2b)$; $(S1+S2a)$ = hydrocarbons thermally distilled from the rock (mg HC/g rock); S2b = hydrocarbons generated by pyrolytic degradation of the kerogen during Rock-Eval pyrolysis (mg HC/g rock).

4.2.1. Disequilibrium compaction

Rapid sedimentation at a greater rate than 1 mm/yr had already produced overpressure in many sedimentary basins worldwide (Hubbert and Rubey, 1959; Fertl, 1976; Tingay et al., 2013). When we rapidly load low permeability sediments, the fluids in the pores cannot escape and are subject to some of the overlying sediment load. In this case, a pore pressure exceeding the hydrostatic pressure develops. Disequilibrium compaction is the main origin of overpressure in rapidly deposited fine-grained systems such as deltas (Osborne and Swarbrick, 1997; Opara, 2010; Li et al., 2020). However, the overpressure size created by the increasing vertical load is limited. It cannot exceed the applied stress. So, the overpressure caused by loading disequilibrium compaction sometimes displays a nearly lithostatic pore pressure increase (Dickinson, 1953; Lahann and Swarbrick, 2011).

The curve of Fig. 4 shows the change in the sedimentation rate in southern Tunisia. According to this curve of sedimentation rates, we can distinguish different Triassic to Jurassic intervals showing periods of:

- Rather slow sedimentation rates because of carbonate platform environment during the Aptian-Albian;
- A high sedimentation rate during the late Cretaceous;
- A halt of sedimentation since the early Tertiary marked by a major unconformity. This coincides with the end of the subsidence and the onset of tectonic compression. Then, the compressive tectonics increased remarkably by the Miocene and Quaternary.

As a result, two main periods of active subsidence were identified across Ghadames basin sedimentation: the first was during the Jurassic period (with significant peaks during the Liassic and the Malm), while the second was recorded during the Cenomanian-Turonian interval.

During these periods, overpressure should have been created, but because of the lack of the real size of subsidence and average rocks' permeability, it is difficult to estimate how important it was. Therefore, starting from the late Cretaceous, there was no sedimentation could create further pore pressure buildup.

4.2.2. Hydrocarbon generation and cracking of oil to gas

Depending on the temperature, time, and pressure, Kerogen changes into coal expelling oil and gas. Kerogen's extra hydrocarbon fluids' volume in source rocks formations can cause overpressure in low permeability conditions (Swarbrick and Osborne, 1998; Swarbrick et al., 2001; Tingay et al., 2013). However, this mechanism could only be a principal cause when the TOC content in a source rock is high and reaches a thermal maturity stage. In their model, Luo and Vasseur (1996) suggested that the critical TOC needed to generate overpressure should be greater than 10% in the oil window and just 1% in the gas windows.

The southern Tunisia study area belongs to the north-African Saharan hydrocarbon province. Therefore, we conducted geochemical analyses on 25 cutting samples from Well-1 to evaluate source rock potential and thermal maturity in the drilled formations. Rock-eval Pyrolysis, Total organic carbons (TOC), bitumen extraction and liquid chromatography were carried out and revealed geochemical changes with the depth (Akrouit et al., 2011, Fig. 5).

The TOC contents in samples (Jr5 to Tr7) from the Late Triassic-Middle Jurassic overpressure is generally less than 1% and (from 0.2% to 0.9%) and have low Tmax values (337 °C–350 °C), suggesting an immature stage.

As a result, in the overpressure during the Triassic-Jurassic interval, we noticed the absence of effective organic materials. Besides, burial

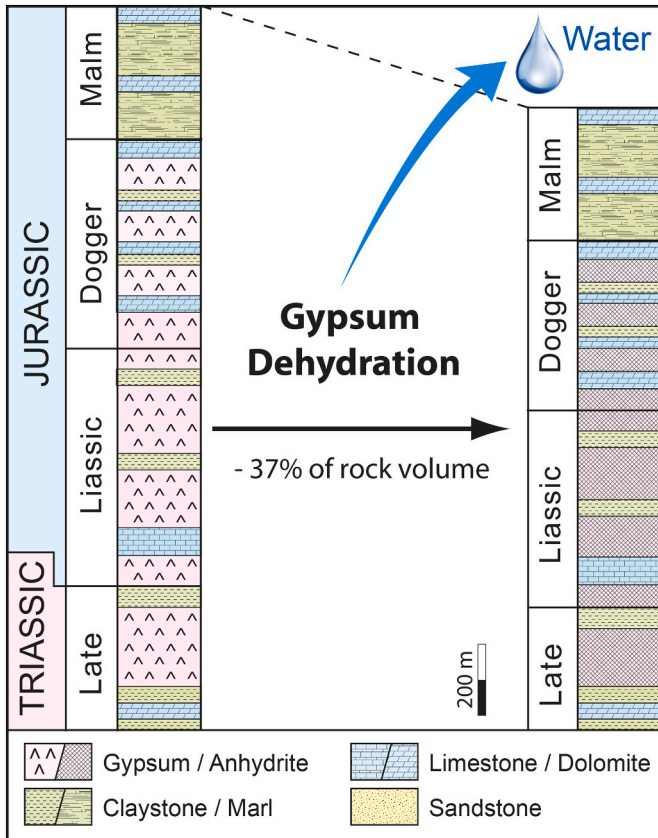


Fig. 6. Gypsum to anhydrite transformation, dehydration reaction leads to 30% decrease of the volume rocks and thickness. This decrease is accompanied by huge water volumes creation expelled into the porosity of the rock and creating quick and high overpressures' amplitude.

was not fully achieved to reach the oil window. So, source rock could not be a possible mechanism to explain the late Triassic-middle Jurassic overpressure.

Moreover, the geochemical analysis confirms the absence of any traces of migrating hydrocarbons. The normal faults could have been the paths that allowed the hydrocarbons migration affecting all the Triassic and Jurassic series. Many authors confirmed that these normal faults are the main pathway for hydrocarbon transported from Paleozoic source rocks to Paleozoic and Triassic reservoirs (Acheche et al., 2001; Underdown and Redfern, 2008; Akrouit et al., 2012). But all oil and gas reservoirs are located beneath the overpressure interval even though the same fault pathways do exist at the top of the Jurassic. This confirms that the overpressure held all hydrocarbons beneath by forming an effective hydraulic barrier against upward migration (Akrouit et al., 2012).

4.2.3. Gypsum dehydration

The chemical transformation from gypsum to anhydrite called dehydration can cause high overpressure (Ciarapica and Passeri, 1976; Lugli, 2001). During this reaction, large volumes of water are released, leading to a decrease in the formation volume. Dehydration is most commonly responsible for abnormal high pressures in halite/anhydrite sequences. The carbonates and shale intercalations in this interval play the role of drains. When diagenetic changes take place, water is produced. Several works settled the temperature conditions for this transformation at around 45 °C. Therefore, this occurred at less than 200 m in a high geothermal gradient (Warren, 2006) and between 600 and 800 m in a normal geothermal gradient (Murray, 1964; Kasprzyk, 1995; Braithwaite et al., 2004; Warren, 2006).

The Late Triassic-Early Jurassic evaporites interval comprises a thick sequence (from 1300 to 2000 m) made up of massive anhydrites and salts, thin claystone beds and locally some dolostones. Gypsum forms the thickest cumulative lithology in the late Triassic-early Jurassic age. The sedimentary environment was probably a shallow marine with gentle continuous subsidence. During the burial, gypsum becomes unstable (Fig. 6), and the dehydration reaction begins $CaSO_4 \cdot 2H_2O$ (gypsum)/

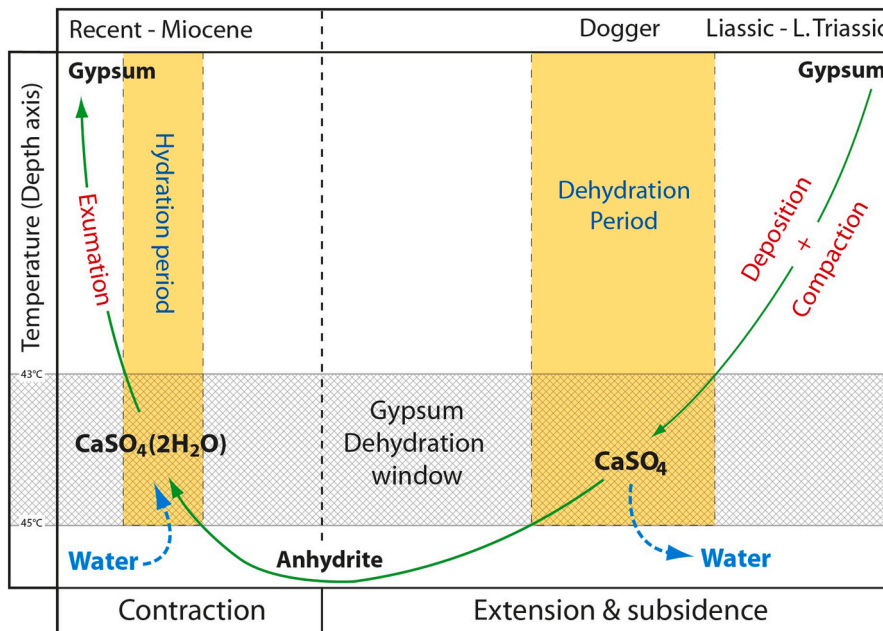


Fig. 7. Schematic diagram showing gypsum transformation throughout diagenetic cycle. Dehydration and hydration occur at 43 °C–45 °C temperature, which corresponds to around 500–700 m depth in normal geothermal gradient basins.

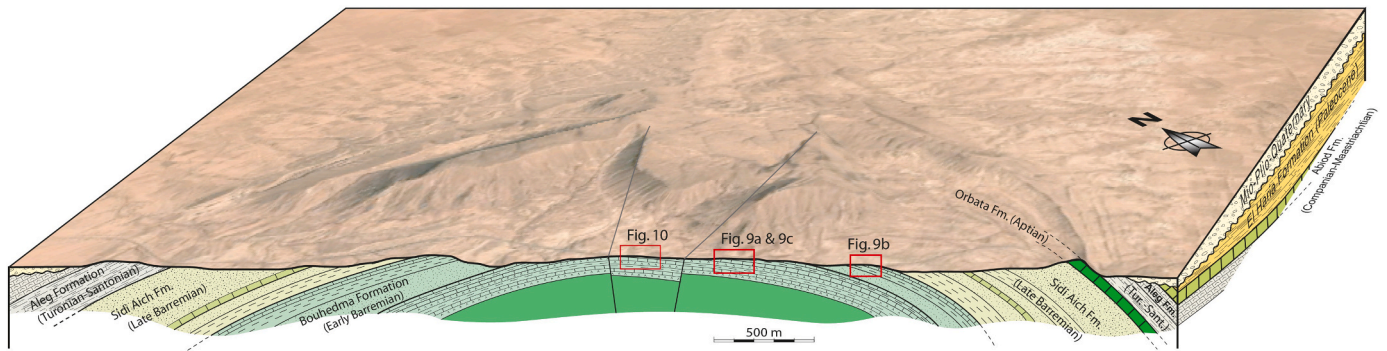


Fig. 8. A 3D sketch of the Zemlet El Beidha anticline geometry and positions of measured sites (location of photographs).

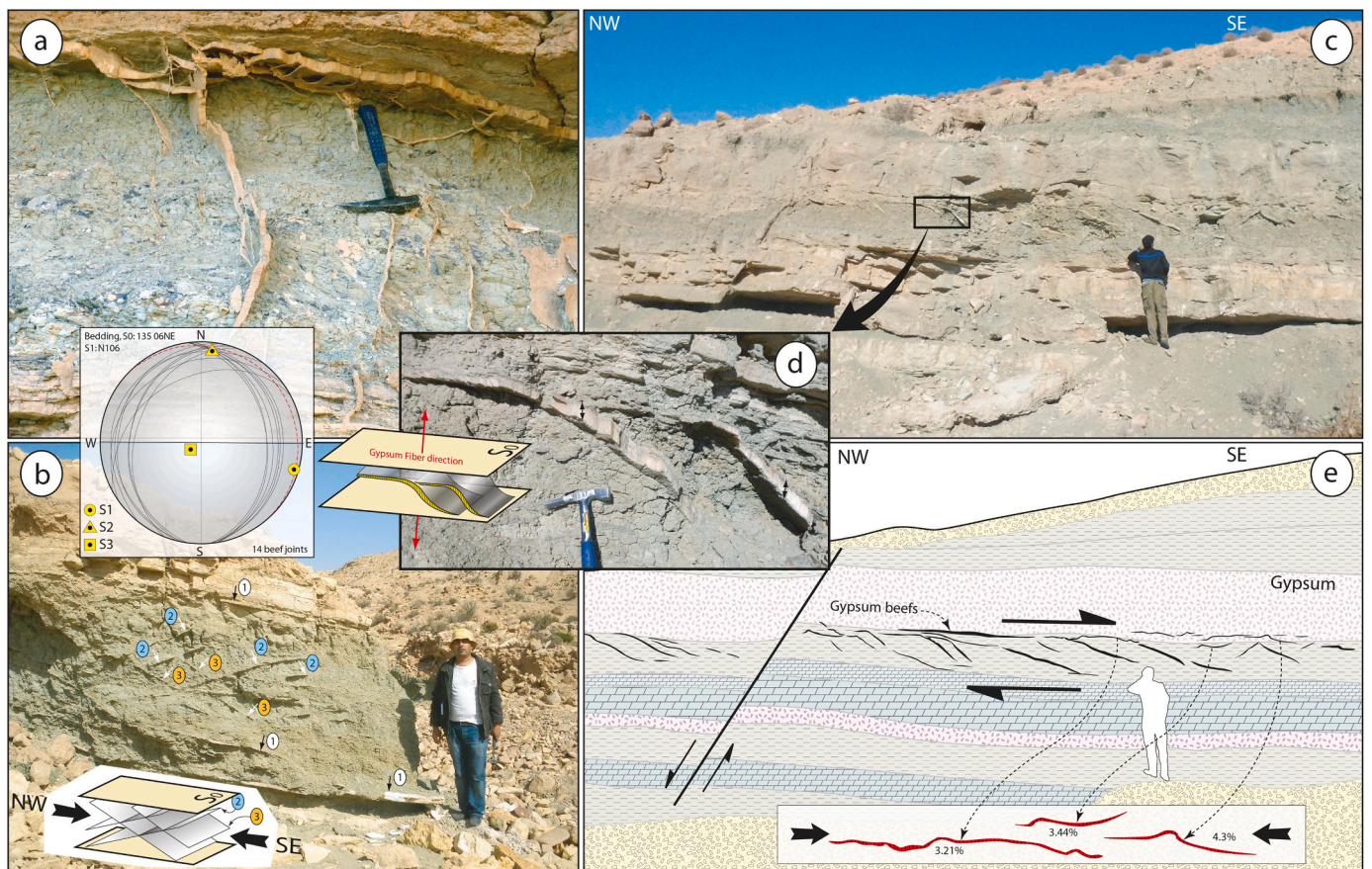


Fig. 9. Photographs of a cliff showing gypsum veins and gypsum beef joints organised in sigmoid shape. a: Claystone bed crossed by gypsum veins which are connected to horizontal gypsum beef joints, b: (1) represents a parallel to bed gypsum beef filled with transverse gypsum fibres; (2) and (3) are conjugate sets of simple shear joints pointing out an NW-SE shortening, this stress direction is consistent with folding stress as shown in stereograms projection in (b), c & e: Photograph and interpretation of gypsum sigmoid veins and horizontal parallel to bed tension gypsum beef joints. Sigmoid joints are created by simple shear in a fold flank. The beef joints show a shortening rate of deformation of about 3.2–4.3%. d: Zoom on (c) photo showing continuity of the gypsum fibres between oblique veins to the parallel to bed beef joints; this indicates that they are contemporaneous.

CaSO_4 (anhydrites) + $2\text{H}_2\text{O}$ (Murray, 1964). The gypsum dehydration reaction has a positive Clapeyron slope. The produced fluid volume increased ($\Delta V_{\text{fluid}} = +37\%$) whereas the solids volume decreased by 30% as a consequence of the dehydration phenomenon (Shearman et al., 1972; Jowett et al., 1993). So, if we suppose the geothermal gradient was at least equal to the present-day, the gypsum transformation into anhydrite would have created great overpressure (Fig. 6). In this case, overpressure would have occurred at least since the Dogger time (Fig. 7).

4.2.4. Tectonic stress

Tectonic loading is a proven cause of overpressure buildup (e.g., Higgins and Saunders, 1974; Unruh et al., 1992a,b; Davis et al., 1983; Byerlee, 1990, 1993; Neuzil, 1995; Yassir and Addis, 2002; Adouani et al., 2020). Some examples include Trinidad (Higgins and Saunders, 1974), Papua New Guinea (Hennig et al., 2002), California (Unruh et al., 1992a,b) and the Gulf of Mexico or in Alaska (Hottman et al., 1979). The effect of tectonic stress is similar to that of strata overburden. It causes horizontal compaction and decreases the porosity (Yassir and Bell, 1996; Obradors-Prats et al., 2016). The effect of compaction and compressive



Fig. 10. Photograph of an anticline hinge and showing tectonic features. (a): frequent small fractures and hydroplastic perturbations (evidence of clay injection) above normal fault of about 2 m displacement, (b): small graben with 20 cm maximum displacement showing high pitch striation.

tectonic stress is massive fluid expulsion that will create overpressure for certain permeability/time ratios.

In the studied region, extensive tectonics dominated the entire Mesozoic age. But from Tertiary, major compressive phases started and led to the North African Atlas thrust and fold belt creation. Several studies have proved that tectonic stress in southern Tunisia is mainly Quaternary in age (Swezey, 1996; Bouaziz et al., 2002, 2003; Ahmadi et al., 2006, 2013). In addition, several authors assigned the present-day

seismicity to the active compressive tectonics (Dlala and Hfaiedh, 1993; Mejri et al., 2010).

In order to highlight potential overpressure features or tracers, we performed a fieldwork campaign. The studied region consists of the Jebel Zemlet El Beida that was the closest to the Saharan platform. It is a NE-SW oriented anticline cored with the Early Cretaceous series. The NW-SE geological cross-section of Fig. 8 shows many unconformities. The first is a post-Aptian unconformity interpreted by Gharbi et al. (2012) as being caused by active extension tectonics that created tilted blocs and grabens. The second major unconformity is the Mio-Plio-Quaternary. This discontinuity is overlaid by siliciclastic sediments resulting from the anticline relief erosion and dates back to the same time of the compressive event.

At the start of the southeastern flank, near the anticline hinge, the deepest outcropping Formation (upper Bouhedma Formation, Early Barremian) shows fibrous gypsum veins and sigmoid joints with specific directions (Fig. 9). These veins are connected to gypsum beefs that are parallel to beds (Fig. 9a & d). This suggests that both the veins and beef joints are contemporaneous. All the studied joints display fibres direction at a right angle to bed surfaces S_0 (Fig. 9d). They are locally organised into conjugate sets with sharp angle highlighting consistent shortening direction with the anticline structure (Fig. 9c). The gypsum beefs themselves are folded in some places, signalling a posterior compression to their creation (Fig. 9c & e).

We noted a normal fault with directions and striations pointing out NE-SW extensive stress in the anticline hinge. We assign this field scale faults to a folding-related structure type: outer hinge (Fig. 10b). With this deformation, we saw important local damage located precisely above the normal fault (Fig. 10a). We interpret this geometry as a hydroplastic deformation resulting from overpressure sudden unload due to contemporaneous normal fault motion. So, we assume that local

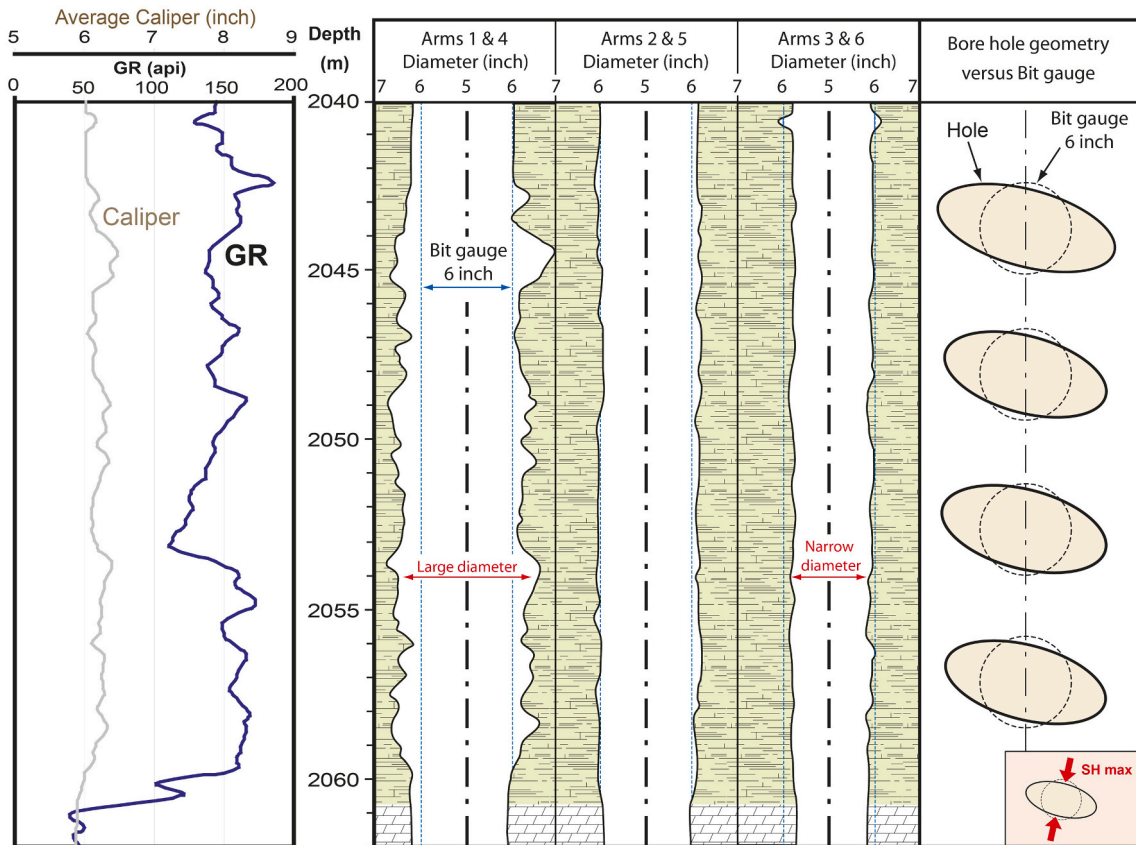


Fig. 11. Logs of 6 arm Caliper data showing differential wellbore diameters. Differential caliper attests of an active compressive tectonic stress being applied on wellbore. Note: none oriented caliper.

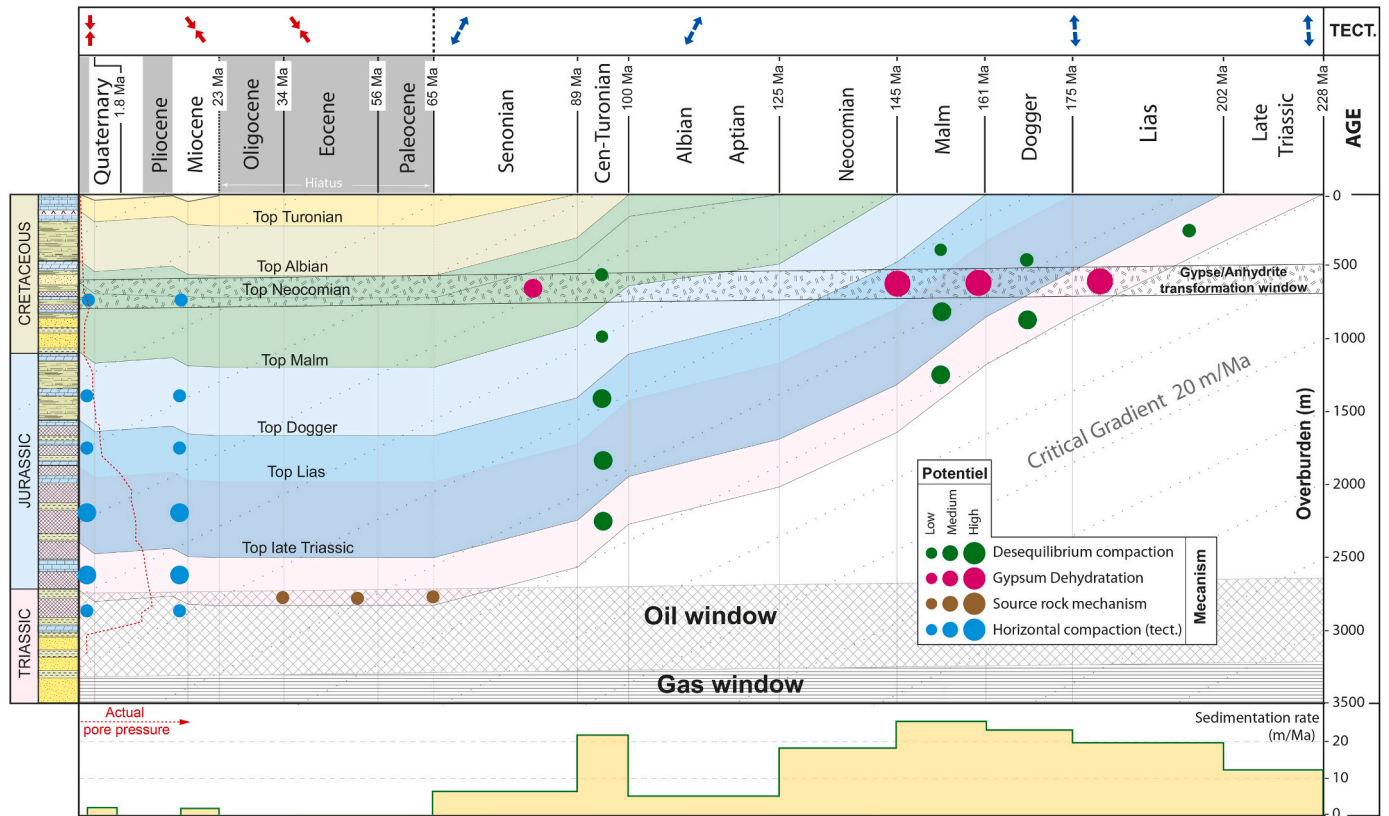


Fig. 12. One-dimensional overburden model displaying overpressure generative conditions and prospecting actual and paleo-overpressures. First, overpressure build-up occurred during the Lias when the thick gypsum of the Late Triassic reached the gypsum-anhydrite transformation window. Sedimentation rates were increasing since the Late Triassic with a maximum rate during the Late Jurassic. This led to an overpressure build-up that was added to the overpressure caused by gypsum transformation over this period. In the Cenomanian Turonian times, an increase in the sedimentation rate created an overpressure in the impermeable units. In the Tertiary, two major tectonic compressive events took place, the first was during the late Messinian-Tortonian, and the second was post-early Quaternary and still active to present-day. The effect of that compressive tectonics regime is create overpressure in impermeable sedimentary intervals.

overpressure can be purged by opening a way between permeable and impermeable beds by faulting. The sudden unload of overpressure water through these normal faults could have created these injected clays (Fig. 10a).

In the southern Tunisian platform, the caliper data in many oil wells (electric logging measuring a well-diameter in many diagonals) showed differential washouts (Fig. 11). The differential caving signals that wellbore was under active tectonic stress, proving that the influence of the compressive stress affected the entire study area.

5. Interpretation and discussion

We built an overburden diagram on which we plotted the thicknesses curves, revealed by depths axis, versus a horizontal time-scale representing ages (Fig. 12). In this model, we displayed all possible origins of overpressure:

1) The mineral transformation window is reached when we fulfil the needed diagenetic conditions. In our case, gypsum/anhydrite transformation is possible when temperatures reach 45 °C (Olgaard et al., 1995). This condition becomes valid at a depth interval of around 600–700 m based on the present-day low geothermal gradient (less than 1 °C/100 ft). Therefore, at the Triassic-Jurassic times, the geothermal gradient did not reach the desired values. However, all signs support a higher geothermal gradient than the present-day because of the active rifting geodynamics during early Mesozoic. So, we expect the temperature to reach 45 °C at shallower depths. Thus; we plotted a slightly slanted interval called gypsum/anhydrite transformation window.

2) Hydrocarbon generation needs pressure and temperature conditions that are satisfied at 2700 m and deeper. This depth is considered as the beginning of the oil window. The Gas window will follow the oil window directly or it may somehow overlap with it at some intervals. For the studied basin, the Triassic-Jurassic age rocks reached the oil window fairly at its top, as proven by the geochemical analysis. So, the gas window is still much deeper than all Mesozoic formations in Ghadames basin.

3) When plotting the depth curve versus age, we notice that the curve slope correlated with the sedimentation rate (Fig. 12). This figure shows the ages that are likely to have produced a fluid overpressure by compaction disequilibrium. We admit that the sedimentation rate study does have weaknesses due to our use of an average rate covering the ages as we have no intermediate accurate dating. This will lead to an important smoothing of some higher subsidence period inside the ages. In our study, however, we can confirm the absence of any important subsidence during the Tertiary and Quaternary periods.

4) The first column (TECT.) in the below Fig. 12, describes the tectonic history of the basin. This enables the reader to distinguish the epoch during which a compressive tectonic mechanism is involved in overpressure creation.

The study of mineral transformation, especially the dehydration reaction, showed that all conditions were fulfilled to create a high overpressure since the middle Jurassic age. On the other hand, the study of the sedimentation rates suggests that two main periods had recorded enough subsidence to create effective overpressure in formation pores: the Jurassic and the interval Cenomanian-Turonian. Nevertheless, the

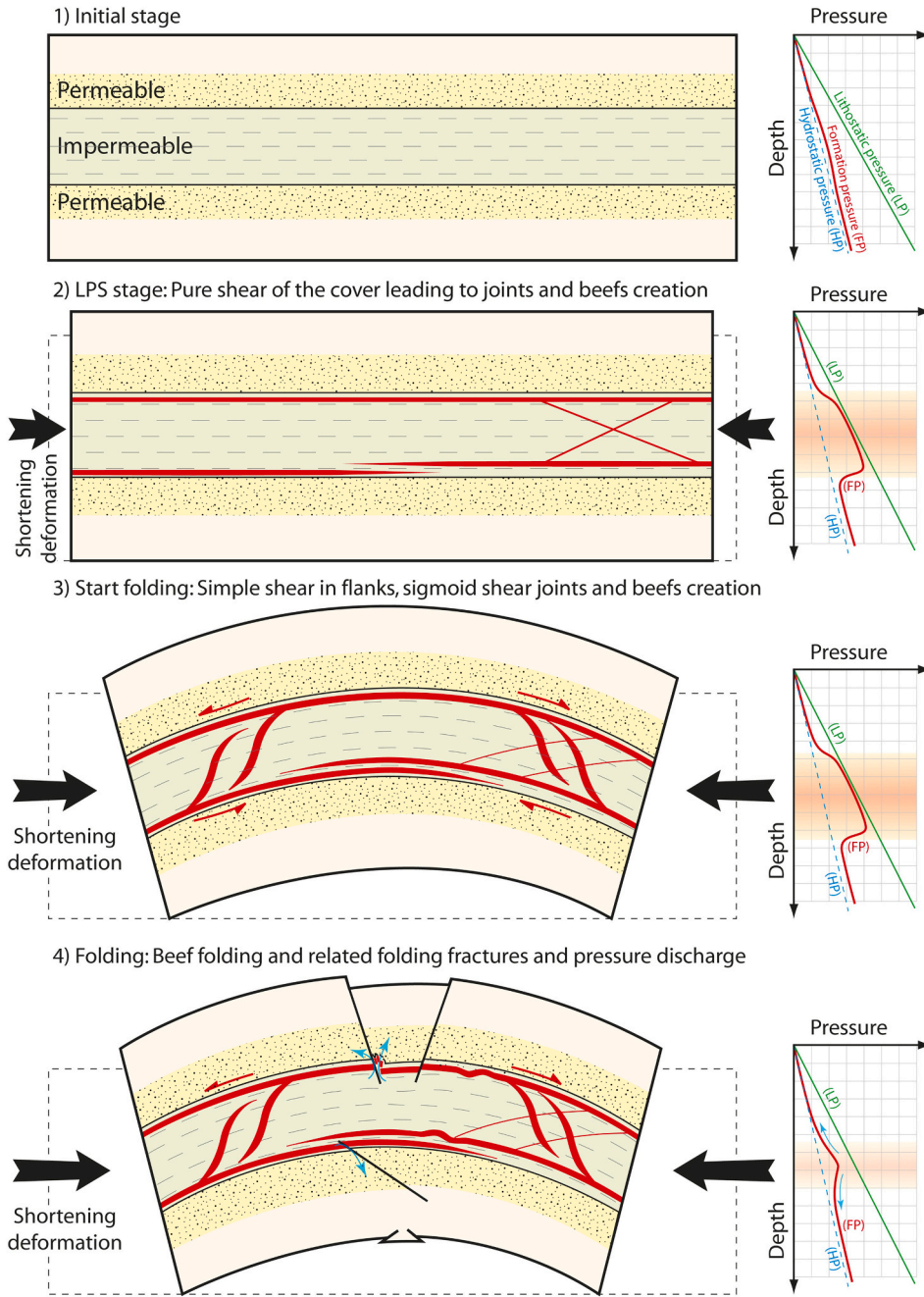


Fig. 13. Model explaining the deformation kinematics in the Zemlet El Beidha anticline and its relationship with pore pressure generation and depletion. The first stage of deformation (2) consisting of pure shear or layer parallel shortening (LPS) creating faults and gypsum beef joints. Conjugate sets of shear fractures could also be generated. At this stage, already overpressure is created. The second phase of deformation started with folding (3). Pure shear and beef creation could continue, but locally simple shear in flanks create sigmoid gypsum veins. At this stage, we think that overpressure is the greatest. With folding growth (4), other related fractures such as outer hinge normal faults and fold core erosion helps in water discharge and pressure depletion. Locally compressive tectonics could create small folded shapes on beef joints.

question to address in the following is: has the produced overpressure remained trapped in the Jurassic or Turonian formations until the present day?

To answer this question, a simple calculation based on Darcy's law allows deducing the necessary time to drain water volumes through one square meter (1 m^2) surface of rocks with different permeabilities. The results in this study indicates that 30 m^3 needs 1 Ma to cross 1 m^2 of low permeability rocks (10^{-10} mD).

So, according to this analysis, it seems impossible to keep overpressure in any sedimentary rocks for more than 10 Ma when the originating mechanism wears off. This involves the fact that the present-day overpressure cannot be explained through older origins than the Late Miocene. Thus, we can assume that the gypsum dehydration and sediment compaction could have resulted from a paleo-overpressure but cannot be the mechanism responsible for the present-day overpressure.

Many studies have proved that tectonic stress is active and recent. So,

compressive tectonics could be a potential origin to explain the present-day overpressure in southern Tunisian basins. The observed hydraulic fractures (beef joints and veins) *in situ* are caused by overpressure equal or nearing lithostatic pressure (Hillier and Cosgrove, 2002; Cobbold and Rodrigues, 2007; Rodrigues et al., 2009). Beefs and veins are filled with the same mineral, gypsum fibres, that always grow in the same direction. This allows us to confirm that both beefs and veins are contemporaneous. The veins geometry and arrangement with the fold flanks can be interpreted as consequent to folding. In fact, simple shear expected in fold flanks can create the sigmoid veins shape. In our case study, a dextral simple shear in the southeastern flank fitted with this model. In another site, a conjugate set of fractures pointed out the same shortening direction consistent with the folding direction (Fig. 9). Therefore, we can assume that the compressive tectonic creates great overpressure and leads to hydraulic fractures such as gypsum beefs and slanting veins.

Nevertheless, since there is no overpressure evidence in outcrops, the interesting questions to answer is: when and how has this large overpressure been depleted?

In exhumated rocks, overpressure could not occur, and these rocks rather reflect hydrostatic pressure. But when a folding occurred, we may assume that deformation caused overpressure in impermeable formations. The folding process itself creates its own fractures, such as outer hinge extensions revealed by field-scale normal faults. These faults can create a pathway between overpressure impermeable beds and permeable drained beds. The sudden water exhaust through these faults creates specific compressive figures (Fig. 10) with important local damage.

We consequently propose the following model (Fig. 13) to explain the field observations:

- When compressive tectonics started, the first stage of deformation, called LPS, led to fracture creation. These fractures could be horizontal veins (Gypsum beef veins) or conjugate sets of shear joints.
- During the first folding stages, the local simple shear in fold flanks generates sigmoidal veins.
- During the growth of folds, structures such as tension joints or normal faults were created in the outer hinge area. These structures will give pathways to overpressure depletion by connecting different beds. Locally we can note water exhaust structures. At this stage, unless the sealing formation is thick enough, overpressure vanishes progressively. If the compressive tectonic continues, we may see folded beef joints. The mineral (anhydrite/gypsum or calcite) that fills the beefs could not accommodate the deformation in the same way as their hosting bed (claystone or mal).

6. Conclusion

We studied pore pressure profiles in southern Tunisian basins and highlighted high amplitude overpressure in the middle-Jurassic-late Triassic series.

The analysis of all possible overpressure mechanisms suggests that compressive tectonics is the most probable cause of the present-day overpressure remarked in southern Tunisia. At a regional scale, this overpressure effectively contributed to the trapping of oil and gas by making a hydraulic barrier to upward migration. However, many other overpressure intervals should have been created in the past due to other mechanisms such as gypsum dehydration and disequilibrium compaction.

The adopted method based on one-dimensional overburden diagram could be generalised to all sedimentary basins in order to study the possible causes of overpressures. This method helps avoid major drilling problems such as blowouts caused by unexpected overpressure reservoirs and all related effects on health and the environment. This model could also predict paleo-overpressures and helps understand the pore pressure history and possible relation to hydrocarbon accumulations (expelling, migration and trapping). Nevertheless, all key intervals such as mineral transformations or oil and gas windows should be adapted to the local field conditions. The modelling parameters depend on background information about the basin geothermic gradient, diagenesis and tectonic history.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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