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REGULAR ARTICLE

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Anatomy and evolution of the Astoin diapiric complex, sub-Alpine fold-and-thrust belt (France)

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Abstract – The structure of the southwestern branch of the Alpine orogen is affected by the extensive Late Triassic evaporites. These evaporites have been involved in polyphased salt tectonics since the early Liassic, coeval with the Tethyan rifting, and are the décollement level for thrusts in the external parts during Alpine orogeny. The role of salt tectonics in this branch of the Alpine arc is re-evaluated in order to determine the relative importance of early deformation related to salt motion with respect to deformation related to main Alpine compressional events. This paper focuses on one structure identified as diapiric since the 1930's: the Astoin diapir (Goguel, 1939). Analysis of geological maps together with new field work have allowed to better define diapirism in the Upper Triassic evaporites outcrops around Astoin. Study of the diapir and the surrounding depocenters reveals a major involvement of salt in the structuration of the area, since the Liassic. Several salt ridges are linked to a main diapiric structure, explaining why we call it the "diapiric complex" of Astoin. Salt tectonics was initiated during the Liassic rifting, and a few locations show evidence of reactive diapirism whereas in others evidence of passive diapirism as early as the Liassic is seen. Passive diapirism continued during the post-rift stage of Alpine margin history in the Late Jurassic and Cretaceous when an allochthonous salt sheet was emplaced. Diapirism also occurred during the Oligocene while the Alpine foreland basin was developing in this part of the European margin of the Alps. Serial interpretative cross-sections have been drawn in order to illustrate the lateral variations of diapirism and structural style. Sequential evolutions for each cross-section are proposed to reconstruct the diapiric complex evolution through time. The Astoin diapir shows a complex structural framework with an important along-strike variation of diapiric activity. Most of the geometries are inherited from salt tectonics that occurred during extension, and in some places these early structures are overprinted by Alpine compressional structures.

Keywords: French Alps / Digne Nappe / salt tectonics / diapir / structural inheritance / tethyan rifting

Résumé – La structure des Alpes Occidentales Méridionales est affectée par les évaporites du Trias Supérieur. Celles-ci sont impliquées dans une activité salifère polyphasée depuis le rifting téthysien au Lias et ont joué le rôle de niveau de décollement pour les chevauchements des zones externes durant l'orogénèse alpine. L'importance de la tectonique salifère dans les Alpes Occidentales Méridionales est réévaluée dans le but de différencier la part de la structuration liée à l'activité salifère précoce de celle liée à la compression alpine en se basant sur une structure identifiée comme diapirique depuis les années 1930 : le diapir d'Astoin (Goguel, 1939). Une analyse cartographique associée à des observations de terrain ont permis de mieux définir le diapirisme lié aux évaporites du Trias Supérieur dans la région d'Astoin. L'étude du diapir et des dépôtcentres associés révèle le rôle majeur des évaporites dans la structuration de la zone, et ce depuis le Lias. La zone est organisée en rides salifères se connectant à une structure diapirique principale, c'est pourquoi nous l'appelons le complexe diapirique d'Astoin. La tectonique salifère s'est amorcée en réaction au rifting liasique. Certaines structures sont réactives et relatives au rifting tandis que certaines structures démontrent un diapirisme passif dès le Lias. Ce diapirisme passif s'est poursuivi durant le stade post-rift de la marge alpine durant le Jurassique Moyen et Supérieur ainsi que durant le Crétacé, probablement à l'origine de la mise en place d'une nappe de sel allochtone. Certaines structures mettent en évidence un

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diapirisme encore actif à l'Oligocène durant la compression alpine. Des coupes structurales évolutives à travers le complexe diapirique sont proposées pour retracer l'évolution de la structure qui montre un agencement structural complexe avec une importante variation latérale de l'activité diapirique. La plupart des géométries observées sont héritées de la tectonique salifère mésozoïque, et dans certaines zones ces géométries sont recoupées par des structures compressives liées à l'orogénèse alpine.

Mots clés : Alpes françaises / nappe de Digne / tectonique salifère / diapir / héritage structural / rifting téthysien

1 Introduction

In the Western Alps, the Late Triassic (Carnian–Norian) evaporites are known to be the major décollement level of the external alpine fold-and-thrust belt (Fry, 1989; Gidon and Pairis, 1992; Lickorish and Ford, 1998). From the very early stages of the Alpine history, however, there is evidence of salt tectonics which has created an important structural inheritance (Goguel, 1939; Lapparent, 1940; Graciansky *et al.*, 1986; Dardeau and Graciansky, 1990; Dardeau *et al.*, 1990; Graham *et al.*, 2012; Célini *et al.*, 2020).

Pre-existing salt horizons and salt structures are key elements in mountain building processes. If a salt body remains planar, it acts as an efficient décollement which affects both the shape and the internal structure of the orogenic wedge (*e.g.* Davis and Engelder, 1985; Costa and Vendeville, 2002). If early salt structures (diapirs or walls, and associated sedimentary structures such as minibasins, hooks, wedges, and megaflaps) formed before the compression, the mechanical architecture of the sedimentary pile and its evolution during shortening will be considerably modified. At the small scale, early salt structures influence the internal structure of the growing compressional belt by (1) accommodating shortening through squeezing (as in the Flinders range in Australia or the La Popa basin in Mexico) (Rowan and Vendeville, 2006; Callot *et al.*, 2007, 2012), (2) controlling distribution and style of folding (as in the Zagros fold-and-thrust belt in Iran) (Jahani *et al.*, 2009; Callot *et al.*, 2012; Fernandez and Kaus, 2014), (3) controlling the fault geometry inside the orogenic wedge, thrusts using preferentially weak salt structures to reach shallower levels (as in the SW French Alps or the Northern Calcareous Alps in the Austrian part of the Alpine orogen) (Dardeau and Graciansky, 1990; Dardeau *et al.*, 1990; Graham *et al.*, 2012; Granado *et al.*, 2019; Célini *et al.*, 2020) and (4) being reactivated and resulting in syn-compressional salt tectonics, such as in the Sivas basin in Turkey (Ringenbach *et al.*, 2013; Callot *et al.*, 2014; Kergaravat *et al.*, 2016; Legeay *et al.*, 2018, 2019).

The structural style and the mechanical architecture of fold-and-thrust belts developed on salt are controlled partly by the down-dip and along strike heterogeneity of the salt. One of the major controlling factors of that lateral variability is the thickness of the salt layer. A thick salt layer will favour detachment folding, diapir growth and/or reactivation with the occurrence of both hinterland and foreland verging thrusts, and preservation of the early structures within the sedimentary package (Davis and Engelder, 1985; Stewart and Clark, 1999; Costa and Vendeville, 2002). It is thus of prime importance to properly evaluate the sedimentary as well as structural inheritance of the salt structures involved in the development of a fold-and-thrust belt, the evolution of which should be evaluated in the light of the salt basin shape and the distribution of salt structures.

Early salt structuration has been described in the Baronnies, the Provence fold-and-thrust belt, the Alpes-Maritimes, the Briançonnais area and recently in the Digne Nappe area (Fig. 1) (Graciansky *et al.*, 1986; Dardeau and Graciansky, 1990; Dardeau *et al.*, 1990; Graham *et al.*, 2012; Espurt *et al.*, 2019; Granado *et al.*, 2019; Célini *et al.*, 2020). In the Digne Nappe area the important role of salt in the early structuration of the sub-Alpine thrust front and during the early rifting history is evident (Graham *et al.*, 2012; Célini *et al.*, 2020). Salt structures of the Digne Nappe region were both related to downbuilding in thick salt area, as well as reactive structures initiated by the Tethyan Liassic rifting. Most of them were still active during the early passive margin stage, and continued to evolve during the whole Alpine history. They played an important role during Alpine compression by accommodating shortening (Graciansky *et al.*, 1986; Dardeau and Graciansky, 1990; Dardeau *et al.*, 1990; Graham *et al.*, 2012; Célini *et al.*, 2020).

The evolution of salt structures observed in the field is usually, by necessity, depicted through cross-sections a 2D/time perspective only. Offshore, 3D seismic datasets allow a real 3D/time investigation of the salt structures and associated depocenters. (Rowan *et al.*, 2012; Hearon *et al.*, 2014; Martín-Martín *et al.*, 2017; Escosa *et al.*, 2019). In this paper remarkable outcrops allow us to describe the 3D lateral variability of the most prominent salt-controlled structure of the Digne area, the Astoin diapir and its surrounding sedimentary basins (Goguel, 1939; Arnaud *et al.*, 1977; Gidon, 1997; Célini *et al.*, 2020). The diapir is located in the Authon–Valavoire thrust sheet near the leading edge of the Digne Nappe and shows high frequency variations of the sedimentary record in response to the diapiric activity, over a few tens of meters (Célini *et al.*, 2020). The adjoining areas seem to contain an important imprint of salt activity still recognised despite the overprint of the Alpine compressional events. The various interpretations of the area produced from mid-1970's to the 1990's underestimated the importance of salt early mobility for two main reasons. As highlighted by Saura *et al.* (2015), the first reason for this is that the trend at that time was thrust tectonics, and salt features such as halokinetic sequences, were most of time interpreted as compressional features (*e.g.* imbricated thrusts geometries) (Ehtechamzadeh Afchar and Gidon, 1974; Arnaud *et al.*, 1977; Arlhac *et al.*, 1983; Gidon and Pairis, 1986; Gidon *et al.*, 1991a; Gidon, 1997). The second reason is that salt tectonics of this area has been known since the 1930's but was considered for a while as Oligocene in age and as minor in comparison with the Alpine compression (Goguel, 1939; Arnaud *et al.*, 1977; Gidon, 1997). We propose a new interpretation of the area combining the important structural inheritance of early salt structures, with the overprint by thrust tectonics of the Alpine compression. We will also focus on the lateral variability of

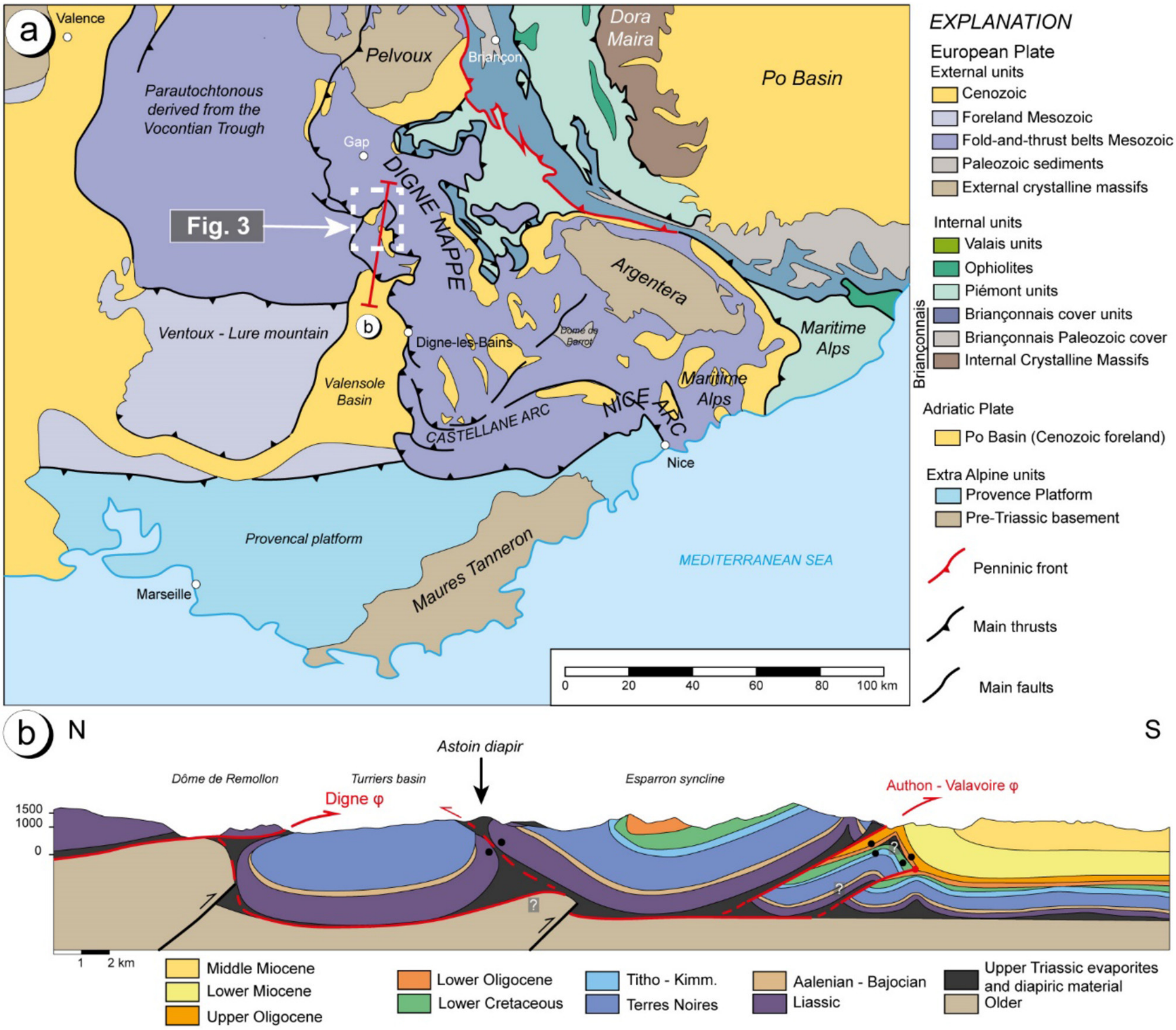

Fig. 1. (a) Structural sketch from SE France modified from Pfiffner (2014). (b) Cross-section of the Digne Nappe near the Astoin diapir (Célini *et al.*, 2020).

salt activity around the Astoin diapir. This study is mainly based on the geological maps at 1/50 000 and published works (Arlhac *et al.*, 1983; Gidon *et al.*, 1991a) together with our own field observations and comparisons with other regions of the world.

2 Geological settings

2.1 Southwestern French Alps framework

The Southwestern French Alps (Fig. 1) are a part of the Alpine arc that resulted from the Europe-Africa convergence and the closure of the Tethys. The SW French Alps represent the western passive margin of the Alpine branch of the Tethyan ocean (Tricart, 1984; Lemoine, 1985; Coward and Dietrich, 1989; Graciansky *et al.*, 1989). The opening of the Alpine Tethys began with the Liassic rifting in relation to the break-up of the Pangea (Dumont, 1988; Coward and Dietrich, 1989; Graciansky *et al.*, 1989; Handy *et al.*, 2010). Continental break-up occurred during the Bajocian and seafloor spreading lasted until the Late Cretaceous to form a narrow Ligurian Tethys ocean (less than 1000 km wide) (Fig. 2).

Convergence started during the Late Cretaceous and the collision stage of the Alpine cycle occurred during the Cenozoic (Coward and Dietrich, 1989; Graciansky *et al.*, 1989; Handy *et al.*, 2010). In the Southwestern French Alps, the collision led to the birth of two major thrust systems, including: the Eocene Embrunais-Ubaye thrust sheets which translated the distal part of the system (*e.g.* Kerckhove, 1969), and the Digne Nappe system, active from the Oligocene to the Pliocene (Apps *et al.*, 2004; Ford *et al.*, 2006), which affected the proximal part and forms the thrust front of this part of the Alps.

The Digne Nappe is 80 km long, with a commonly accepted shortening of 20–25 km towards the SSW-SW (Faucher *et al.*, 1988; Fry, 1989; Ritz, 1992; Ford *et al.*,

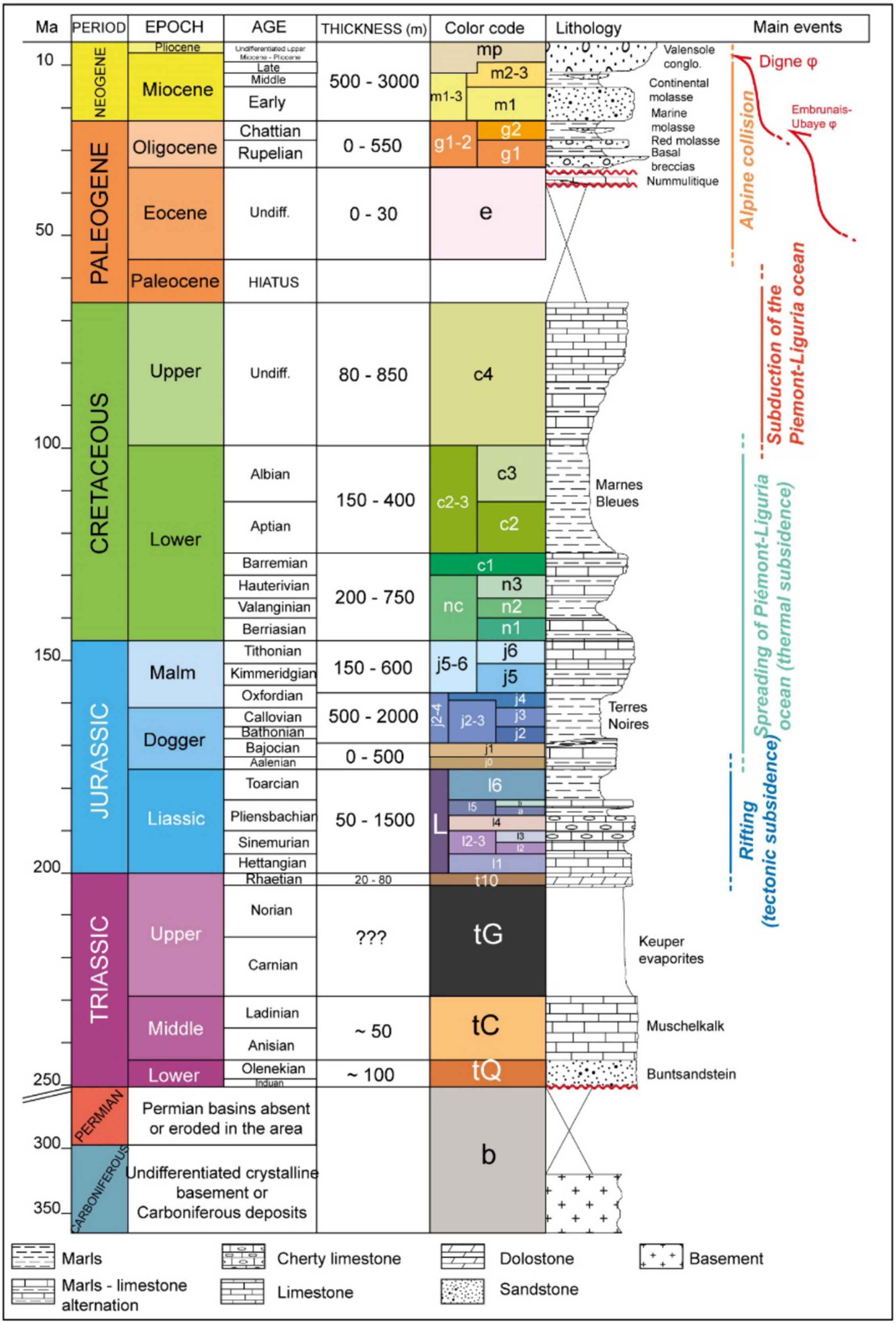

Fig. 2. Stratigraphy of the Astoin diapir area.

1999). It has been emplaced in a continental settings and carried an originally nearly 8 km thick pile of Mesozoic–Cenozoic sediments over the Valensole foreland basin in the Durance valley (Gigot *et al.*, 1974; Crumeyrolle *et al.*, 1991; Gidon and Pairis, 1992; Gidon, 1997; Schwartz *et al.*, 2017). The Authon–Valavoire thrust slice has been emplaced prior to the Digne Nappe *s.s.* over an Oligocene land surface and constitutes its leading edge (Graham *et al.*, 2012). Cross-section in Figure 1b shows an interpretation crossing the study area in which the Mesozoic sedimentary cover was strongly structured by salt tectonics during rift and post-rift periods inducing an important structural inheritance, and where compressional deformation is partly decoupled between the basement and the supra-salt cover (Célini *et al.*, 2020).

2.2 The stratigraphy of the Astoin–Clamensane area

The sub-Alpine stratigraphy has been studied and mapped by geologists for a very long time (*e.g.* Haug, 1891; Goguel, 1939). The Triassic of the area is composed of the classical German Triassic trilogy: the Buntsandstein sandstones (Lower Triassic), the Muschelkalk limestones and dolostones (Middle Triassic) and the Keuper evaporites (Carnian–Norian). This trilogy is capped by the Rhaetian dolostones, silts and marls that mark the top of the Triassic (*e.g.* Rousset *et al.*, 1983; Gidon *et al.*, 1991a). The local subdivisions of the classical Liassic stratigraphic scale are used in this paper because they highlight lithological changes related to the main rifting stages and to the structure of the rift for each stage (Fig. 2). Thus, when possible, the Sinemurian is divided into the Sinemurian *s.s.* (lower Sinemurian, l2) and the Lotharingian (upper Sinemurian, l3), and the Pliensbachian is divided into the Carixian (lower) and the Domerian (upper) (Fig. 2). The Liassic rifting period is characterised by limestones from Hettangian to the end of the Carixian which is capped by a hardground which marks a sudden deepening of the sedimentary environment. The Domerian and the Toarcian are mainly marl deposits. The general thickness of the Liassic section is 500 m in the Authon–Valavoire thrust sheet. At Turriers, the section is extremely reduced to 50 m or so (the so-called "Turriers-type" or "very reduced" Liassic section, Fig. 4). This reduced Liassic section can also been observed in the Picouse–Valentin sector (Figs. 3 and 4) (Rousset *et al.*, 1983; Gidon and Pairis, 1986; Gidon *et al.*, 1991b; Gidon, 1997). Several outcrops in the area show a reduction of 50 m thick Liassic with many sedimentary gaps (Fig. 4). In the Digne Nappe the Liassic reaches a thickness of 1000 m in the La Robine syncline near Digne-les-Bains and 1500 m at Remollon (Gidon, 1997).

In this part of the sub-Alpine chains, the Aalenian is only present within the Digne Nappe (Fig. 3). The Bajocian is generally unconformable on the Liassic and is characterised by an alternating limestones and marls. It varies in thickness from zero to 100 m in the Authon–Valavoire thrust sheet and can be up to 150 m in the Digne Nappe (Gidon *et al.*, 1991b).

The upper Bajocian to middle Oxfordian is represented by the so-called "Terres Noires". This is a thick marl succession with a few interbedded detritic channels, limestones beds and phosphatic nodules (Gidon and Pairis, 1986). Liassic olistoliths can be found within the Terres Noires in the Turriers basin (Célini *et al.*, 2020), and near the Clamensane fault zone (Fig. 3) (Arnaud *et al.*, 1978b), the emplacement of these is interpreted as resulting from salt tectonics. The thickness of the Terres Noires is variable because it is not only controlled by the passive margin structure (Artru, 1967), but also by salt tectonics (Célini *et al.*, 2020). In the Astoin–Clamensane area the average thickness is 1200 m where the whole section is present but can reach more than 2000 m in some places (Artru, 1967; Gidon and Pairis, 1986; Gidon *et al.*, 1991b).

Deposits younger than the Terres Noires are rare in the Astoin–Clamensane area. They are preserved north of the area in the Turriers basin and south in the Reynier and Esparron synclines (Fig. 3). The Kimmeridgian is characterised by an alternation of marls and limestones below the Tithonian massive limestones. The Early Cretaceous begins with the alternating limestones and marls of the Berriasian, followed by the Valanginian marls (Gidon *et al.*, 1991a, 1991b; Rousset *et al.*, 1983), then a new alternation of marls and limestones of Hauterivian age below Barremian limestones (Rousset *et al.*, 1983; Gidon *et al.*, 1991b). The only Albian strata are represented by the Aubrespin klippe in the Turriers basin north of the Astoin diapir (Fig. 3) (Gidon and Pairis, 1986).

The Upper Cretaceous and Paleocene are missing and the oldest Tertiary sediments present are the Priabonian (Eocene) Globigerina marls and Nummulitic limestones in the north of the area (Gidon, 1997). Oligocene is preserved in the Le Caire valley, the Esparron syncline and a few remnants are found in the Picouse–Valentin sector (Fig. 3). Oligocene strata are the youngest deposits preserved in the area and are mainly continental deposits (Rousset *et al.*, 1983; Gidon *et al.*, 1991b).

2.3 The structure of the Astoin–Clamensane area

The Astoin–Clamensane area is located in the NW part of the Authon–Valavoire thrust sheet, which as previously stated, is the leading edge of the Digne Nappe (Fig. 1). It is bounded to the west by the Vermeil fault and the Clamensane fault zone which probably represent the lateral ramp of the thrust sheet, to the east by the Digne Nappe *s.s.*, to the north by the southern termination of the Turriers basin and to the south by the Esparron syncline (Figs. 3 and 4). The Authon–Clamensane area is characterised mainly by Jurassic deposits with lower Cretaceous rocks preserved in the Esparron syncline and Cenozoic deposits both in the Esparron syncline and in Le Caire valley (Fig. 4).

The amount of displacement on the Authon–Valavoire thrust sheet is uncertain. The southern limit is well constrained but the northern part, between Clamensane and Turriers is much less clear, because there are no clear footwall or hangingwall cut-off (Ehtechamzadeh Afchar and Gidon, 1974; Arnaud *et al.*, 1977; Arlhac *et al.*, 1983; Gidon *et al.*, 1991a; Gidon and Pairis, 1992; Gidon, 1997). Authors defined structural units based on the facies of the Liassic successions (*i.e.* condensed, of normal thickness, or thick basinale) leading to confusing interpretations, requiring many imbricated thrusts and strike-slip relay faults. We have already demonstrated that salt tectonics partly controlled the Liassic facies and thickness distribution (Célini *et al.*, 2020), and proposed that the whole

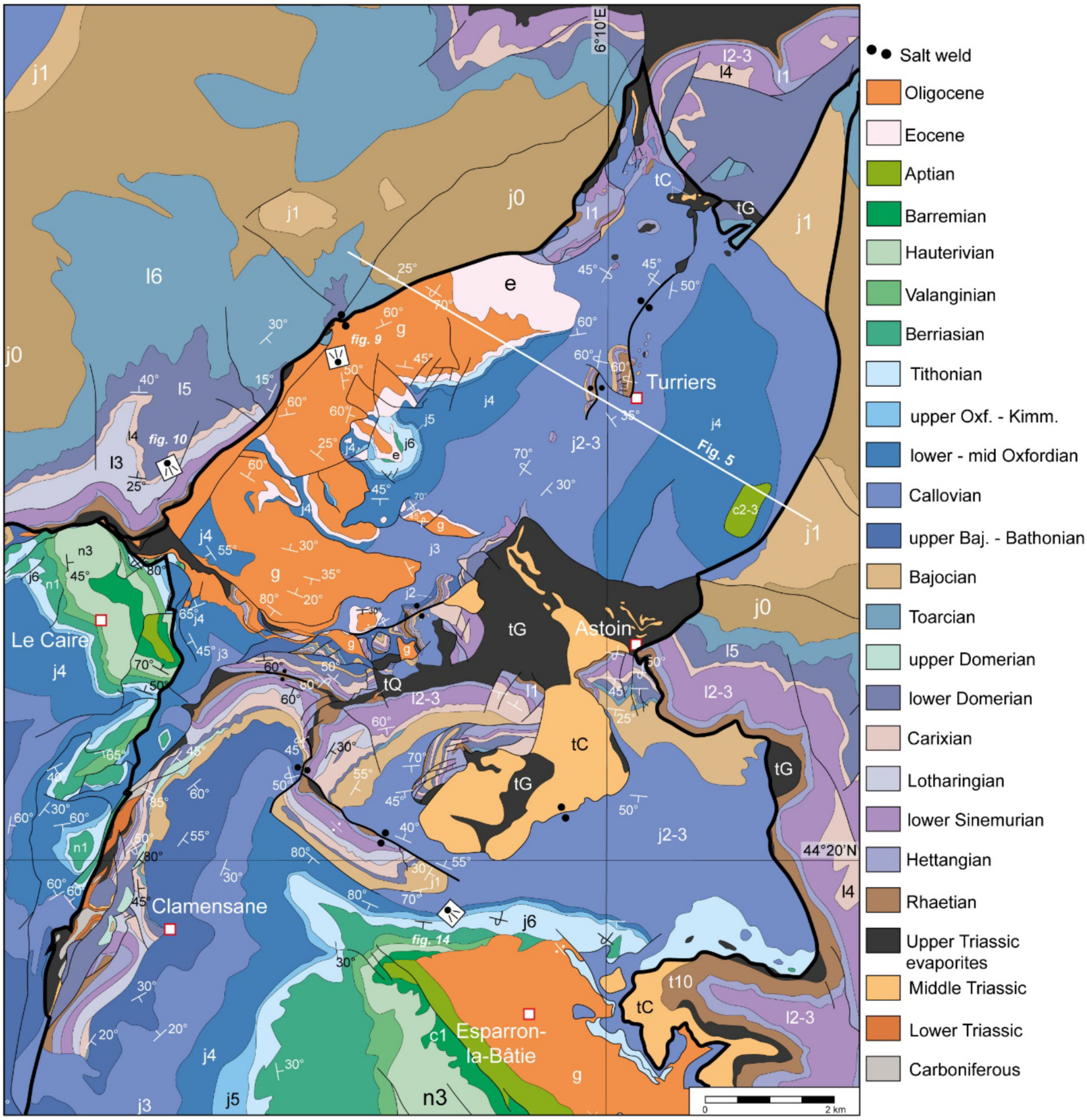

Fig. 3. Geological map of the study area modified and harmonised after the geological maps of France at 1/50 000 from the BRGM.

area from Remollon to the southern edge of the Authon–Valavoire thrust sheet is a single structural unit.

At first order, the area seems to be organised as a succession of synclines, in which mostly the Terres Noires are exposed, and anticlines which present mostly Liassic and Upper Triassic rocks. In some locations older rocks such as Middle and Lower Triassic and, in the Clamensane "lineament", Carboniferous blocks (Fig. 3) (Ehtechamzadeh Afchar and Gidon, 1974; Arnaud *et al.*, 1977, 1978a; Arlhac *et al.*, 1983; Gidon and Pairis, 1985; Gidon *et al.*, 1991a; Gidon, 1997). In these numerous structural interpretations of the area, thrust tectonics does not totally account for the tectonic evolution of that zone (Ehtechamzadeh Afchar and Gidon, 1974; Arnaud *et al.*, 1977; Arlhac *et al.*, 1983; Gidon and Pairis, 1986; Gidon *et al.*, 1991a; Gidon, 1997). Looking more into details, it appears that several locations present diapiric evidence already described, such as the Astoin diapir, or the Clamensane fault zone (Arnaud *et al.*, 1978a, 1978b; Célini *et al.*, 2020).

3 The Astoin diapiric complex

At present day, the main salt structure of the Astoin–Clamensane area is the Astoin diapir itself (Goguel, 1939; Arnaud *et al.*, 1977; Gidon, 1997). The diapir has been developing since the Liassic and reached the seafloor during the Bajocian creating an overturned flap of Hettangian–Sinemurian (Célini *et al.*, 2020), but this structure is not the

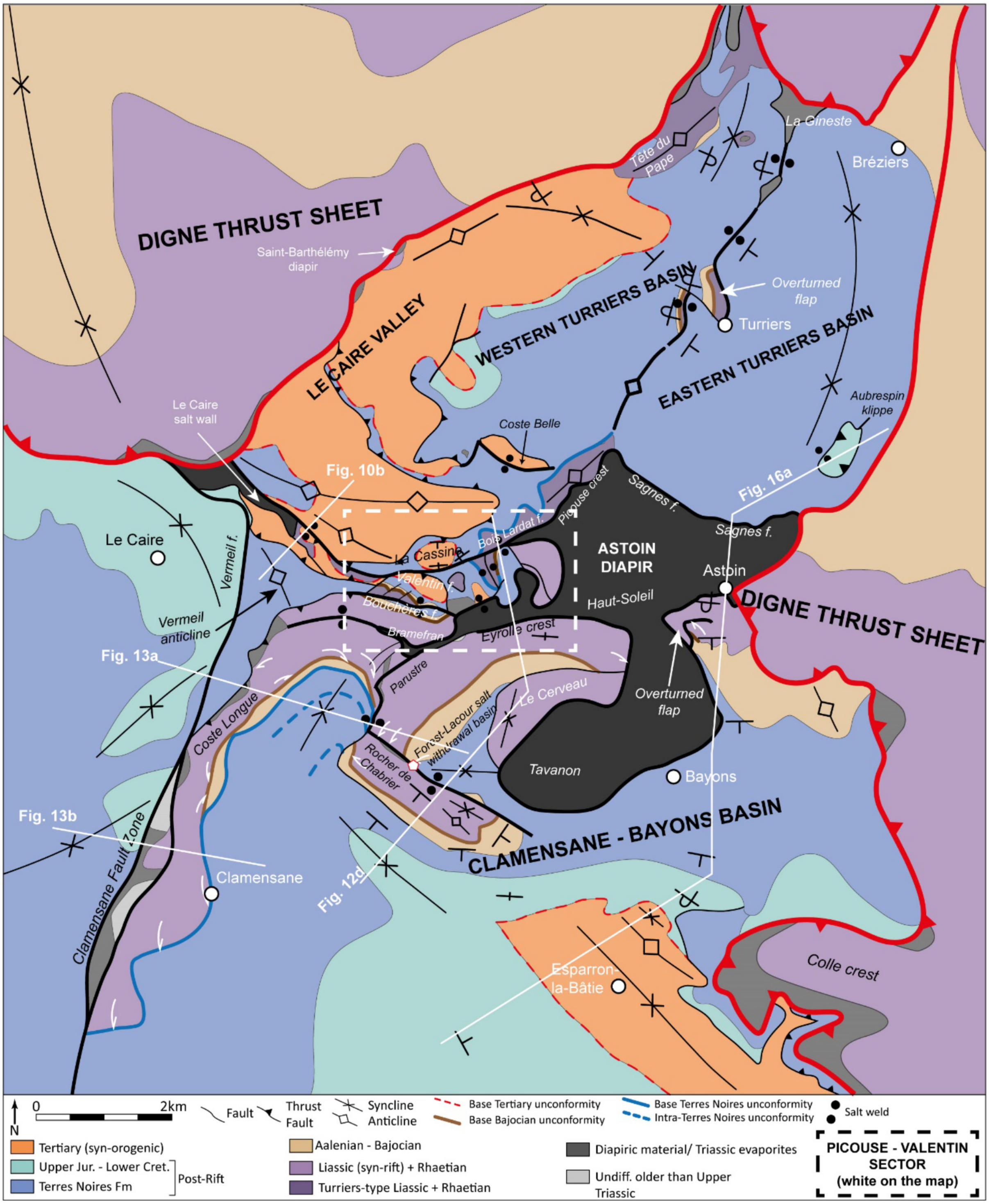

Fig. 4. Structural sketch of the study area with the main locations.

only evidence of active Liassic- to Dogger-in-age salt tectonics in the area. The eastern flank of the diapir is obscured by the Digne Nappe. However, in the Turriers basin, the Clamensane–Bayons basin and the Picouse–Valentin sector (Fig. 4) the stratigraphic response to salt movement can be documented. The northern edge of the Astoin diapir is the Turriers basin and the southern edge is the Clamensane–Bayons basin which stretches from the Clamensane lateral ramp to the eastern exposure of the Digne Nappe (Fig. 4). These basins are pluri-kilometric synforms with a thick Terres Noires development. The nature of the Liassic section in the two areas is very different. The Clamensane–Bayons basin shows the "classical" Liassic section of the Authon–Valavoire thrust sheet (see Sect. 2.3), whereas the Liassic section of the Turriers basin is

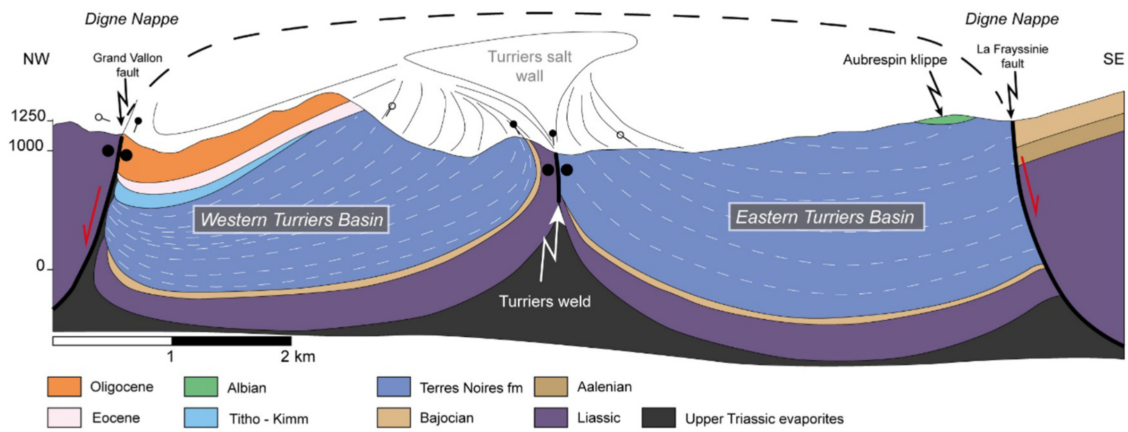

Fig. 5. Cross-section through the Turriers basin, modified from Célini *et al.* (2020). See location of the cross-section in Figure 3.

the "Turriers-type" section which is very reduced and contains many sedimentary gaps.

The diapir itself can be divided into two units: an eastern one located near Astoin and a western one which is the Picouse–Valentin sector (Fig. 4). This contains reduced "Turriers-type" Liassic sections in which the stratigraphic pile shows numerous internal and successive unconformities and presents several vertical contacts that have been interpreted as imbricated thrusts subsequently folded by the Alpine compression (Ehtechamzadeh Afchar and Gidon, 1973, 1974; Arnaud *et al.*, 1977).

3.1 The Turriers basin: northern edge of the Astoin diapir

The Turriers basin is bounded to the west, the north and the east by the Digne Nappe (Fig. 4). To the south, it is bounded by the Sagnes fault, the Picouse crest and the Bois Lardat fault which constitute the northern edge of the Astoin diapir (Fig. 4). The Turriers basin is divided into the western and the eastern sub-basins, separated by the Turriers weld oriented NNE-SSW (Figs. 4 and 5) (Célini *et al.*, 2020). The Eastern Turriers sub-basin is a syncline filled with Terres Noires and containing a klippe of overturned Albian marls, namely the Aubrespin klippe (Figs. 4 and 5) (Gidon and Pairis, 1986). The Western Turriers sub-basin also contains a thick section of Terres Noires and a "Turriers-type" severely thin Liassic section at Turriers and La Garenne which forms the overturned flap of Turriers (Fig. 5) and the Liassic section of the Tête du Pape anticline at the northern termination of the Western Turriers sub-basin (Fig. 4).

3.1.1 The contact between the Turriers basin and the Astoin diapir

The contacts between the two parts of the Turriers basin and the Astoin diapir are the Sagnes fault, the Picouse crest and the Bois Lardat fault (Fig. 4). These structures are discussed separately because the contact between the Turriers basin and the Astoin diapir varies laterally.

3.1.1.1 The Sagnes "fault"

3.1.1.1.1 Data and observations

The Sagnes fault separates the Terres Noires of the Eastern Turriers basin from the Astoin diapir (Upper Triassic evaporites and Middle Triassic limestones and dolostones) (Fig. 6a). The fault is nearly vertical in the east (Fig. 6b), but becomes nearly horizontal in the west near the Picouse crest (Fig. 6c) (Gidon and Pairis, 1986). The horizontal contact of the evaporites above the Terres Noires gives the impression that evaporites have flowed out over the Terres Noires in that location. Gidon (1997) described this contact as a thrust fault that supposedly emplaced Triassic over the Dogger section of the Turriers basin.

3.1.1.1.2 Interpretation

Since the Astoin diapir and the Turriers basin are parts of the Authon–Valavoire thrust sheet (*e.g.* Gidon and Pairis, 1986), and the Turriers basin is the northern depocentre related to the Astoin diapir growth (Célini *et al.*, 2020), we propose that the Sagnes fault constitutes the interface between the diapir and the basin. In the west, the horizontal part of the Sagnes fault with salt above the Terres Noires (Fig. 6c) is easier to explain as a salt sheet or salt overhang. This vertical portion of the fault is topographically higher than the vertical portion of the Sagnes fault in the east (Fig. 6b), so it may be that the horizontal part in the east has been eroded away. The change in dip of the Sagnes fault can also illustrates along-strike variations of the diapiric contact.

3.1.1.2 The Bois Lardat diapir and welds network

3.1.1.2.1 Data and observations

The Bois Lardat fault is the direct lateral continuation of the Picouse crest, and is oriented WNW-ESE (Fig. 7). To the west, it disappears under the hangingwall of the Valentin fault (Fig. 7). The Bois Lardat fault forms the limit of the enigmatic Patassiers structure that on the map (Fig. 7a) looks like a syncline in cross-section (Fig. 8a). The core of the syncline, which is also the base of the stratigraphic pile, abuts against the vertical Bois Lardat fault (Fig. 7a). At the Picouse crest,

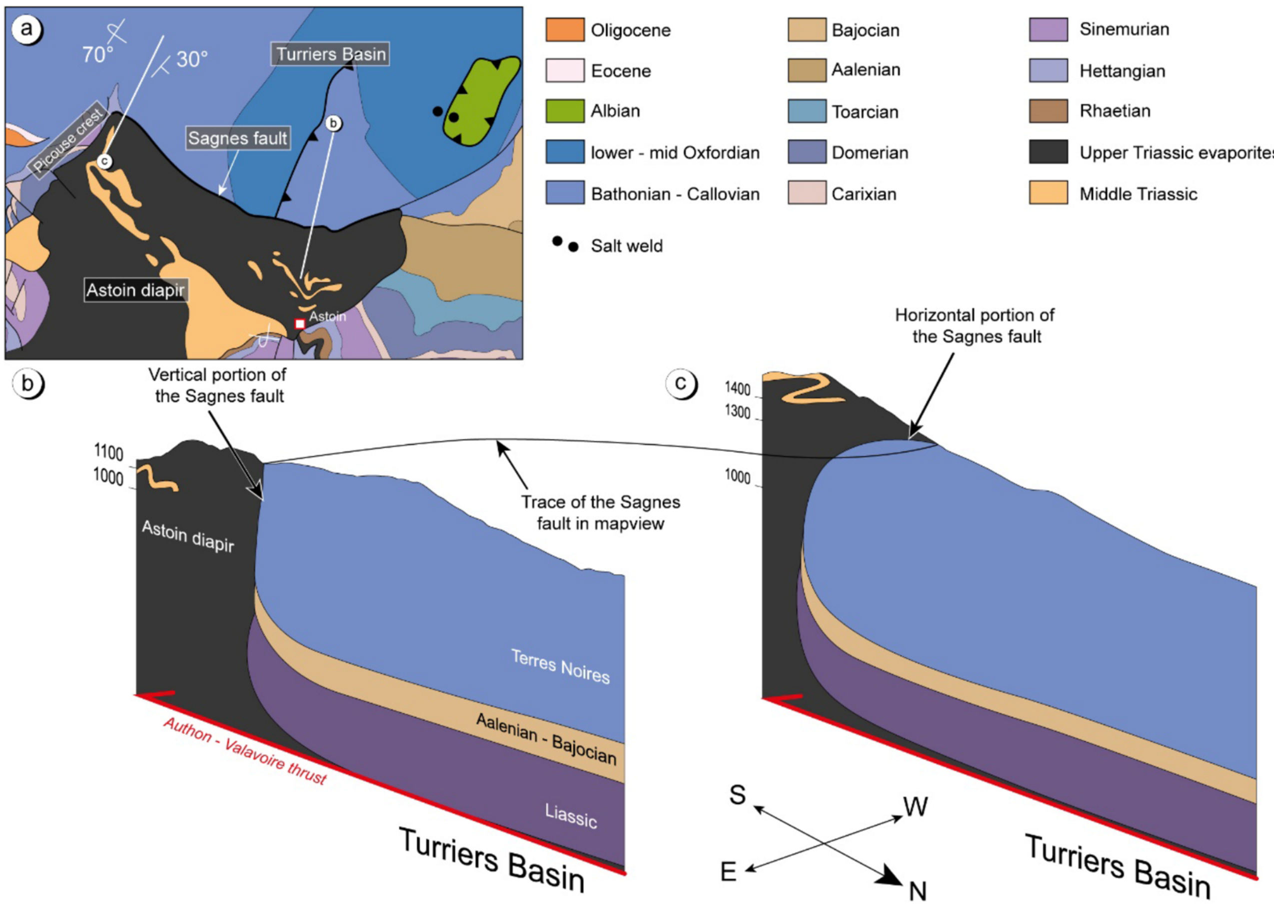

Fig. 6. (a) Zoom of the geological map on the Astoin diapir and the southern termination of the Turriers basin. (b) Interpretative cross-section through the Sagnes fault in the eastern part of the diapir. (c) Interpretative cross-section through the Sagnes fault in the western part of the diapir.

the Terres Noires in the Patassiers syncline lies directly over various levels of the Liassic. In the east, the Callovian lies stratigraphically over the Hettangian further west the Bathonian lies on the Domerian (Figs. 7a and 8a), and the Liassic itself shows successive internal unconformities (Figs. 7a and 8a). To the west, the Terres Noires and more precisely its Callovian interval is overturned against the Bois Lardat fault below the Tertiary deposits of La Cassine (Fig. 8b). Here, Eocene and Oligocene strata form a syncline the southern limb of which is vertical against the Bois Lardat fault (Fig. 8b) (Arnaud *et al.*, 1977).

3.1.1.2.2 Interpretation

Within a few hundreds of meters the Les Patassiers structures shows successive unconformities within the Jurassic sedimentary pile highlighted by pinch outs of a few stages (Fig. 8a). This cannot be explained by Cenozoic Alpine compression nor by Jurassic rifting. We therefore propose that these discontinuities are the result of salt motion during Jurassic times and that the faults are fundamentally salt welds. The Les Patassiers structure is a depocentre that is a part of the Turriers basin, but shows abrupt stratal variations and unconformities within a few hundreds of meters because it was originally located near the crest of the Astoin diapir.

The La Cassine syncline overlies overturned Terres Noires (Fig. 8b) in a manner suggestive of successive halokinetic folds abutting a vertical weld (the Bois Lardat fault). Eocene and Oligocene strata were apparently turned vertical by salt above the Terres Noires that was already overturned by the salt during the Jurassic (Fig. 8b).

The La Cassine and Les Patassiers structures are thus two salt-related structures located directly against the Bois Lardat fault (Fig. 7), which is itself connected to the Astoin diapir. We propose that the Bois Lardat fault is actually a weld which represents the trace of a former salt structure connected to the Astoin diapir (Fig. 7b). The La Cassine syncline demonstrates that salt tectonics continued in the Cenozoic and it is not the only evidence for salt tectonics of this age in the region of the Astoin diapir.

3.1.2 Oligocene salt-controlled structures within the Turriers basin

The northern contact of the Astoin diapir is also the southern termination of the Turriers basin. The nature of the contact between the Turriers basin and the diapir varies laterally and the basin shows evidence of a number of salt-controlled structures, some Jurassic some Tertiary. An interpretation of the southern Turriers basin as a Middle Jurassic overturned megaflap has been proposed (Célini *et al.*, 2020), but the Tertiary salt activity has not been described until now. Tertiary sediments overlie the western part of the Turriers basin.

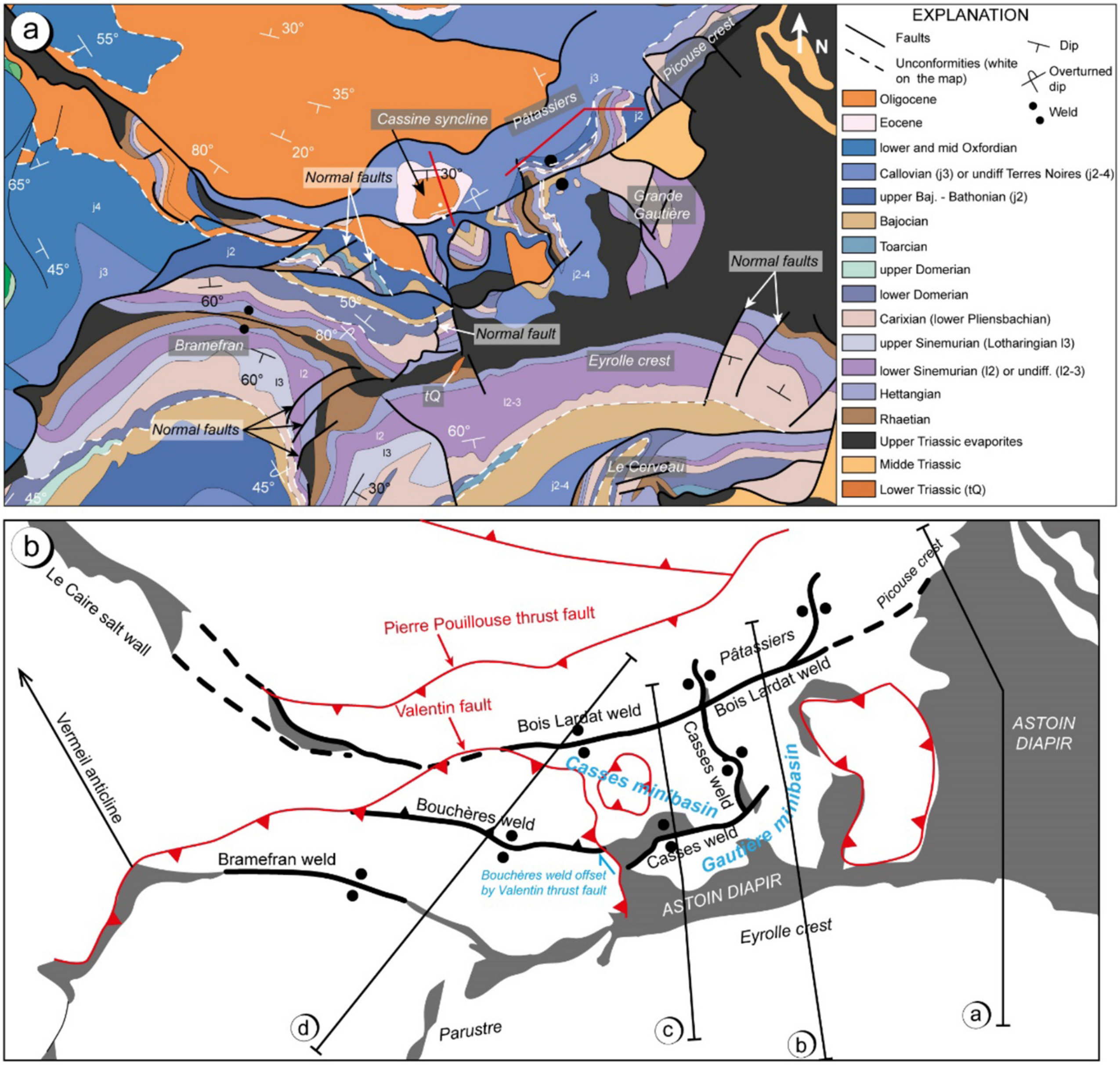

Fig. 7. (a) Geological map of the Picouse–Valentin sector (See location in Fig. 4). (b) Structural sketch of the Picouse–Valentin sector with the main structural relationships (faults and welds). Black lines correspond to the locations of cross-sections in Figure 18.

The NE-SW Le Caire valley (which forms the western limit of the Turriers basin), runs from Le Caire to the Tête du Pape anticline (Fig. 4). Along with the Esparron syncline, it preserves an important thickness of Eocene and (mainly) Oligocene strata. At the base a thin layer (< 50 m) of Eocene, Nummulitic marls and limestones is exposed, unconformable over the Terres Noires or Tithonian–Kimmeridgian (Fig. 3). Post-Oligocene Alpine compression has strongly overprinted that area with the formation of numerous folds and thrusts compatible with the classical NE-SW shortening direction in this part of the Alps. However, two locations in the Le Caire valley expose facies and geometric relations that are better explained by Oligocene salt tectonics. These are the Saint-Barthélémy diapir and the Le Caire salt wall (Fig. 4).

3.1.2.1 The Saint-Barthélémy diapir

Two outcrops of Upper Triassic evaporites occur along the Grand Vallon fault (Fig. 4) which separates the Digne Nappe from the Western Turriers basin. One of these, located next to the Saint-Barthélémy farm, shows evidence of Oligocene salt tectonics, and has briefly been mentioned as diapiric by Ehtechamzadeh Afchar and Gidon (1974). Oligocene strata are highly folded near the diapir, upturned against it and overturned below younger Oligocene strata which overlie them unconformably (Fig. 9). These younger units are more or less flat lying in normal stratigraphic sequence below the Digne Nappe (Fig. 9). White breccia with calcite lies along the unconformity surface and strongly contrasts with the Oligocene red continental shales and sandstones (Fig. 9c). Casts of

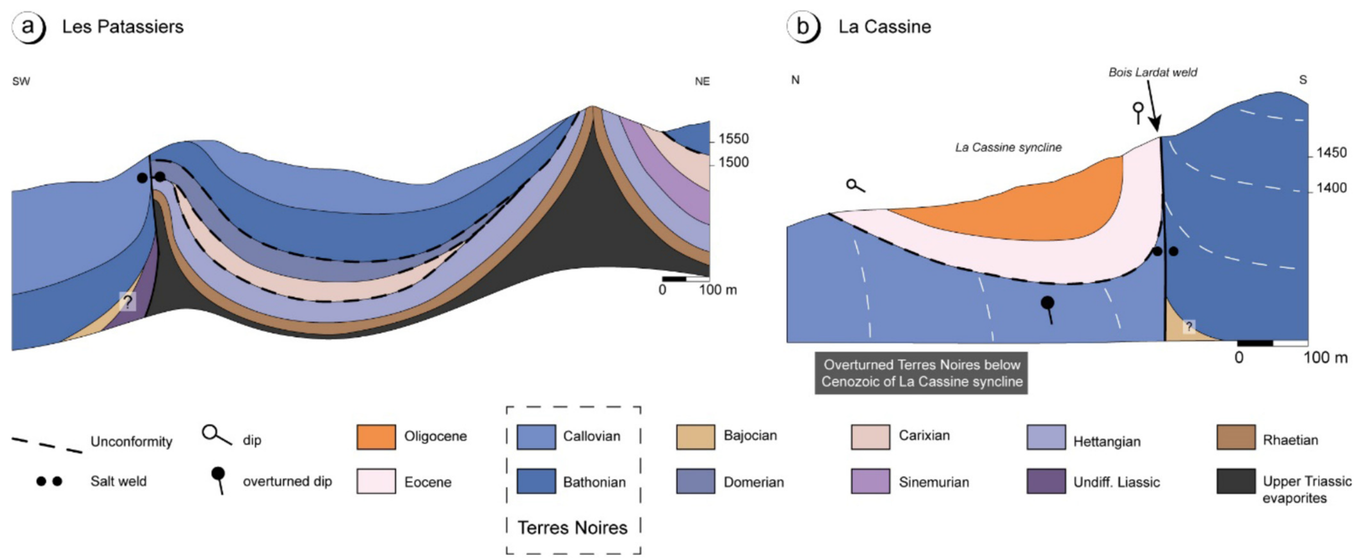

Fig. 8. (a) Interpretative cross-section through the Les Patassiers structure. (b) Cross-section through the Bois Lardat weld and the La Cassine syncline. See location of cross-sections in Figure 7.

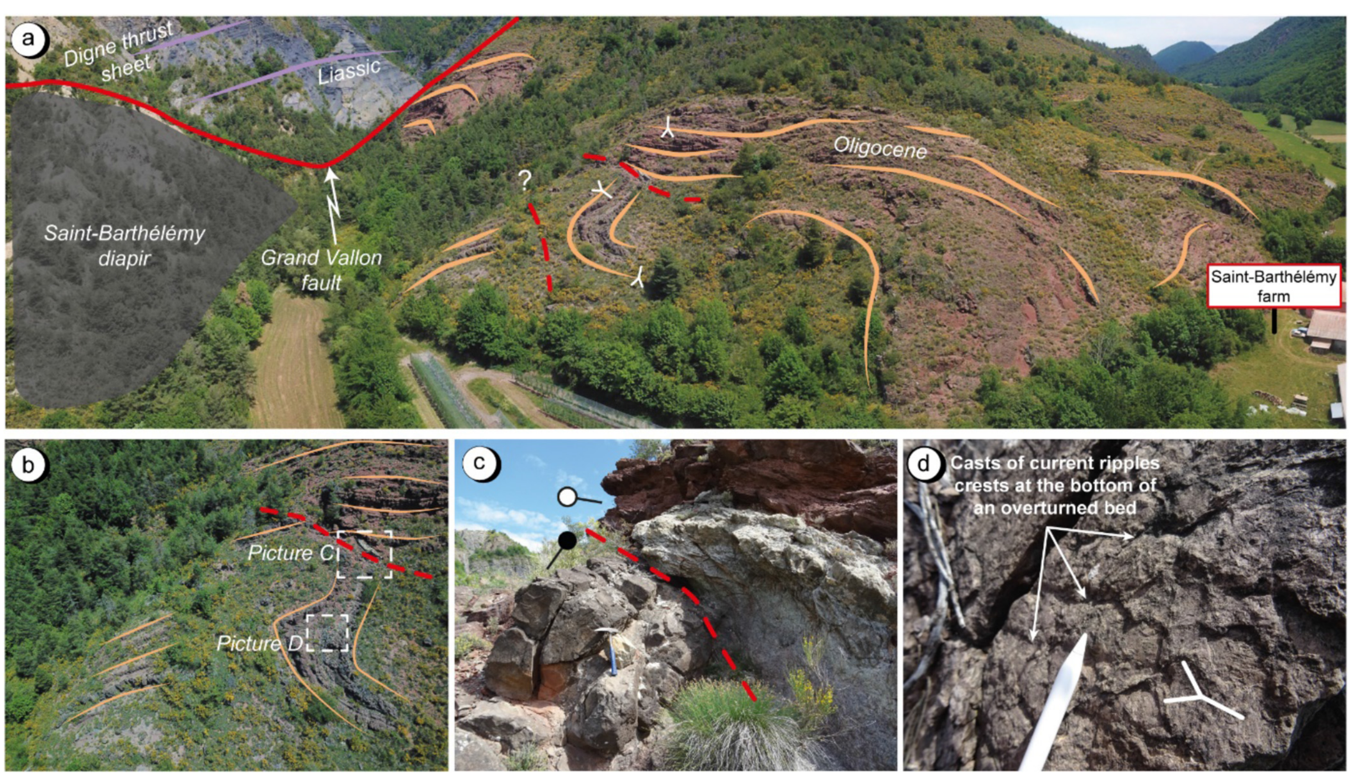

Fig. 9. (a) Photo of the Oligocene strata near the Saint-Barthélémy farm showing the global pattern of the Oligocene which is twice overturned below younger Oligocene, forming two successive hook halokinetic sequences. (b) Zoom on one hook halokinetic sequence showing Oligocene overturned strata below younger Oligocene strata and the unconformity between. (c) Zoom on the unconformity. (d) Picture of casts of the crest of current ripples marks at the bottom of a bed, testifying that the Oligocene is overturned.

current ripples confirms the polarity of the lower beds (Fig. 9d). The whole setting is interpreted as two or more hook halokinetic sequences (Giles and Rowan, 2012). It testifies to the fact that Upper Triassic evaporites remained mobile close to the surface until at least the Oligocene.

3.1.2.2 Le Caire structure: a salt wall active from the Liassic to the Oligocene?

3.1.2.2.1 Data and observations

The Le Caire structure is located (in the Le Caire valley between Le Caire and Faucon-du-Caire) near the contact

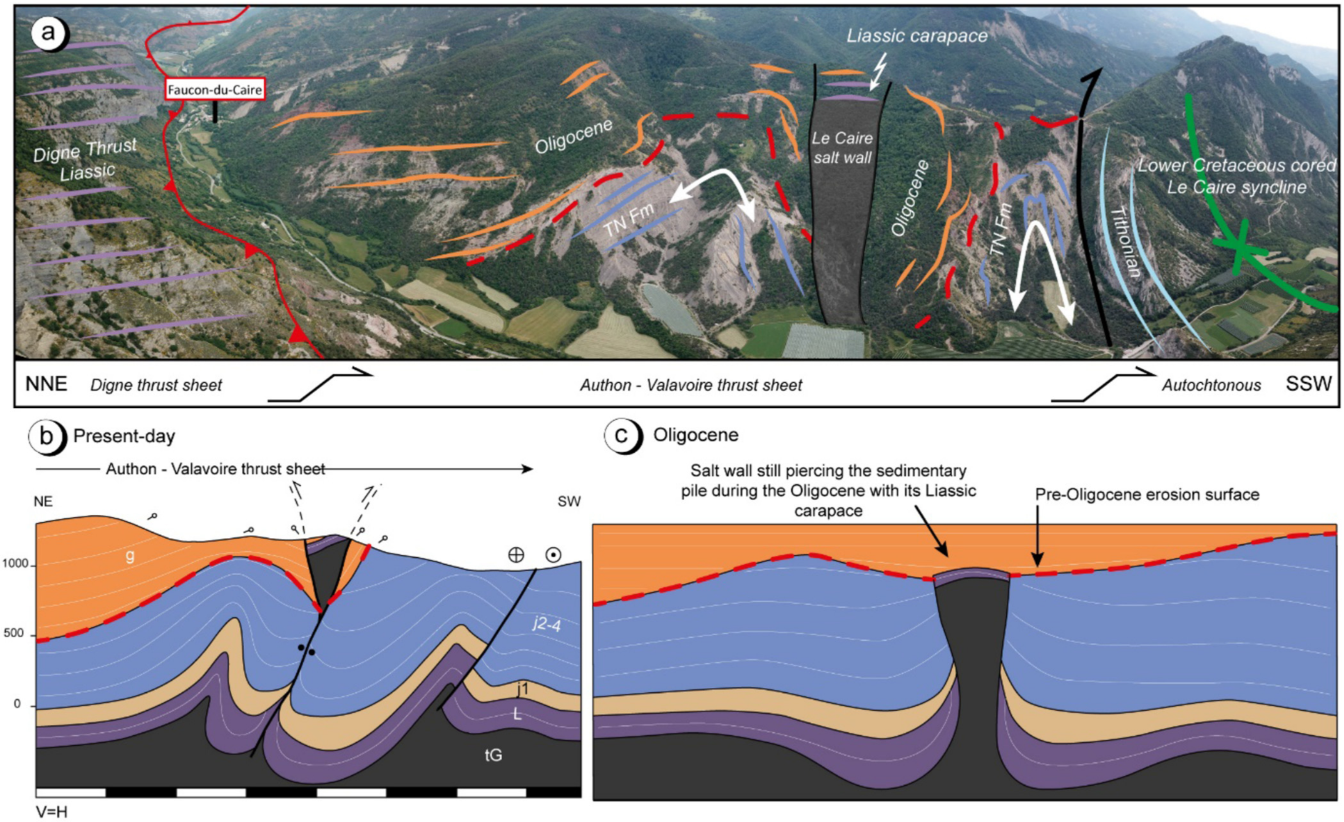

Fig. 10. (a) Panorama of the Le Caire valley showing the Oligocene and the Terres Noires formation strata abutting against the Le Caire salt wall at the boundary between the Authon–Valavoire thrust sheet and the autochtonous. (b) Present day interpretative cross-section through the Le Caire salt wall. (c) Interpretative cross-section during Oligocene of the Le Caire salt wall, showing the Liassic carapace on top of the salt wall.

between the Authon–Valavoire thrust sheet and the autochtonous units (Fig. 4). It is a 3 km long NW-SE oriented fault zone which joins the Bois Lardat weld to the SE and to the NW disappears below the Digne Nappe (Fig. 4), the Digne Nappe which overlies the Authon–Valavoire thrust sheet and partially overlies the autochtonous unit.

The Le Caire structure is composed of Upper Triassic gypsum directly in contact with the Liassic, the Terres Noires or the Oligocene (Fig. 3). In most places, the Oligocene is unconformable on the Terres Noires and in some locations directly on the Liassic (Fig. 4). The Liassic which lies between the Upper Triassic and the Oligocene, is a very reduced section of highly brecciated limestones and dolostones with many sedimentary gaps. In places these rocks look like cargneules.

The important pre-Oligocene erosion reached down to the "Terres Noires" formation and only in one location to the Liassic and the Upper Triassic, implying that the Upper Triassic and Liassic successions were already close to surface before Oligocene deposition. The Oligocene dips towards the Upper Triassic gypsum and abuts against it something that was taken to imply a tectonic contact by Gidon *et al.* (1991a, 1991b).

3.1.2.2.2 *Interpretation*

The relationships described above together with the narrow and elongated shape of the Le Caire structure suggest to us that it must have been a salt wall active from the Liassic to at least the Oligocene (Fig. 10). We propose that the contact between the Oligocene and the evaporites is not a tectonic contact but a diapiric one. The folding of Oligocene strata (Fig. 10) suggests that the salt wall and the adjacent depocenters have been tightened during post-Oligocene compressional events.

In our interpretation the Liassic succession at the top of the salt most probably formed a carapace that remained on top of the salt structure and was still present at the time of Oligocene deposition (Fig. 10). Such preserved carapaces, in contact with younger strata flanking the salt structure have been observed in other localities, especially on seismic from the Northern Gulf of Mexico (see Jackson and Hudec, 2017, p. 153).

The Le Caire structure is located a few hundreds of meters away from the Astoin diapir and seems to form be the western continuation of the Bois Lardat weld. It is therefore reasonable to interpret the Le Caire salt wall as the lateral continuity of the Astoin diapir, a peripheral salt wall connected to the main body of the Astoin diapir. The enormous stratigraphic gap between the Terres Noires and the Oligocene prevents us from understanding how the salt wall evolved during that period. Was it buried during the "Terres Noires" formation and reactivated only at the Oligocene or was it rising during the whole Cretaceous as well?

3.2 The Clamensane–Bayons basin: the southern edge of the Astoin diapir

Near the village of Astoin, the Astoin diapir created an overturned megaflap during the Bajocian and built an

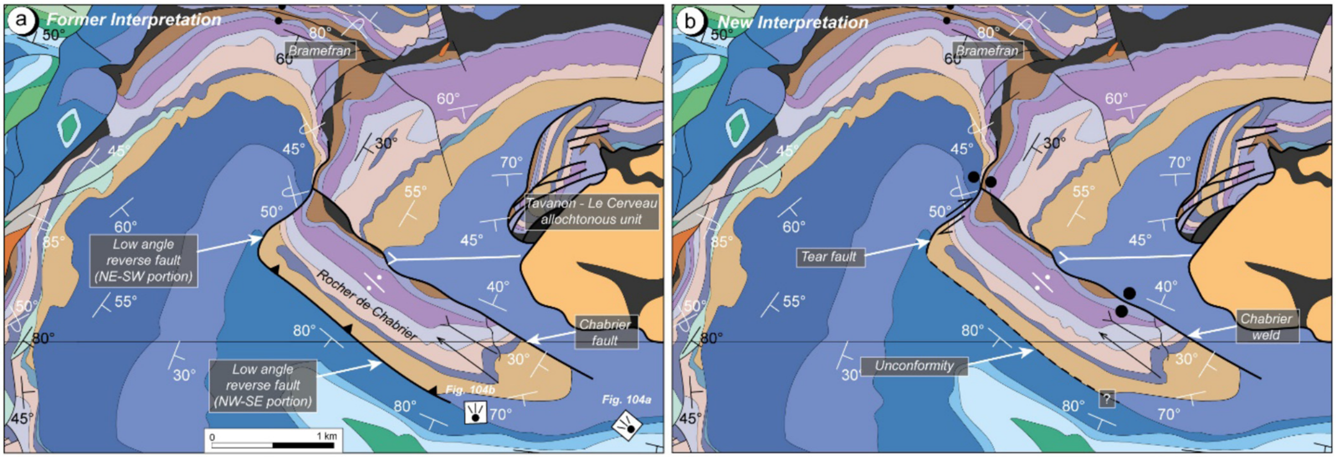

Fig. 11. Zoom on the geological map of Figure 3, focused on the Rocher de Chabrier.

allochthonous salt sheet carrying stringers of Muschelkalk limestones and dolostones (Middle Triassic) towards the surface (Célini *et al.*, 2020). The location of the southern edge of the Astoin diapir is not yet constrained. No overturned flap is observed to the west, therefore the response of the surrounding strata to the diapir development must vary laterally (as was described earlier on the northern contact of the diapir).

3.2.1 The Rocher de Chabrier weld

3.2.1.1 Data and observations

The Rocher de Chabrier is located immediately west of the Forest-Lacour (Fig. 4). It consists in a 2.5 km long nearly vertical Liassic section with remnants of Rhaetian and Carnian–Norian evaporites (Fig. 11a). The Terres Noires succession abuts, thins and locally pinches out along the Rocher de Chabrier. The section is truncated on its SW side by a minor thrust which is at its NW termination oriented NE-SW and nearly flat. To the SE, the fault trace is oriented NW-SE and becomes a vertical contact that follows the Bajocian and Terres Noires stratigraphy (Fig. 11). In the field, it is difficult to identify this structure because the uppermost part of the Terres Noires seems to lie on the Bajocian (Figs. 12a and 12b). On the NE side, the Rocher de Chabrier is bounded by the Chabrier fault (Fig. 11a) which dips steeply towards the NE (~ 80°). East of the Rocher de Chabrier, this fault dies out in the Terres Noires. To the NW, the Chabrier contact joins the NE-SW portion of the low-angle reverse fault described above, and both join the weld of the Bramefran high (Fig. 11a). Along the Chabrier fault, remnants of Upper Triassic gypsum are locally observed (Fig. 11a). NE of the fault, a tight syncline containing rocks ranging in age from Liassic to Terres Noires (Fig. 11a) seems to have been down-thrown by a normal fault.

The Liassic section of the SE termination of the Rocher de Chabrier changes orientation from overturned to the NE to almost vertical to the SW (Figs. 12b and 12c). Between those two dip domains, the Liassic section is tightly folded into a tight syncline anticline pair, both with vertically plunging hinges (Fig. 12). The folds deform only the Liassic and do not affect the younger Bajocian or the Terres Noires which seal the structures (Fig. 12).

3.2.1.2 Interpretations

We interpret the Chabrier vertical section as a vertical megaflap located on the SW side of a former salt-controlled structure. It has been welded by the Alpine compression with a few remnants of evaporites now located in the Chabrier fault zone (Figs. 11a and 12d). The tight Terres Noires syncline on the NE side of the weld is therefore seen as a rim syncline located on the NE flank of the former salt ridge. The SE termination of the Chabrier vertical megaflap was initially adjacent to a salt wall and is comparable with the Gypsum Valley salt wall from the Paradox Basin (SW Colorado, USA) described by Escosa *et al.* (2019). The Charbrier salt wall shows a nearly vertical megaflap developed on the SW side of the salt wall while on the NE side strata are gently upturned (~ 40°) against the Chabrier weld. The strata of the vertical megaflap is analogous with one of the members described by Escosa *et al.* (their Fig. 13) which shows a "constant limb length with gradual decrease in dip along-strike" (Escosa *et al.*, 2019). Unlike the Gypsum Valley salt wall, the Chabrier salt wall has vanished during Alpine compression, so the Chabrier weld has evidently been confused with a counter-regional fault described by Escosa *et al.* (2019). The Chabrier weld can be extended to the SE beyond the termination of the salt wall by a tectonic contact which disappears into the Terres Noires. This tectonic contact is interpreted as the remnant of the counter-regional fault and is now not distinguishable from the weld because of Alpine compression. The Chabrier salt wall, unlike the Gypsum Valley salt wall, does not present any radial faulting, though this maybe due to the difference in scale between both structures. The Gypsum Valley salt wall (35 km long 3.5 km wide) is much larger than the Chabrier salt wall (~ 2 km long and width unknown because the wall is now welded) (Escosa *et al.*, 2019). Another explanation to that difference can be than that the deformation accommodated in the Paradox Basin by the radial faults is accommodated here by the small folds affecting the Liassic (Figs. 12b and 12c).

The geological significance of the low-angle reverse fault (Fig. 11) on the SW side of the Rocher de Chabrier can be discussed in the light of this. The NW-SE oriented portion of the fault seems to be more a sedimentary gap than a reverse fault (Fig. 11b). If this fault really exists, it is difficult to

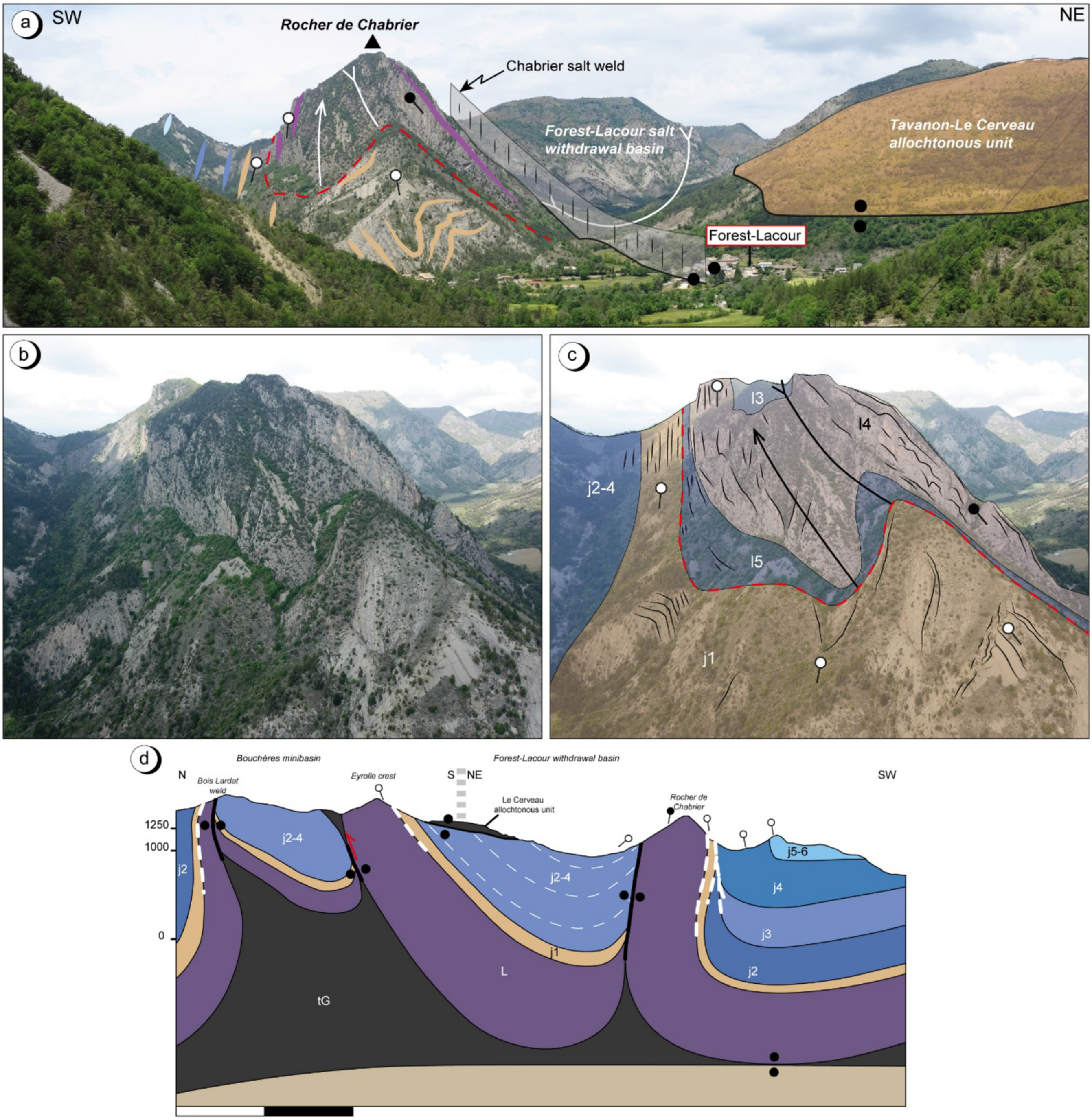

Fig. 12. (a) Interpreted panorama of the Rocher de Chabrier megaflap and the associated Forest-Lacour salt withdrawal basin (rim syncline) both on each side of the vanished Chabrier salt structure. (b) Zoom on the Rocher de Chabrier tight anticline and syncline illustrating the early deformation of the megaflap. (c) Interpreted picture of the Rocher de Chabrier zoom. (d) Interpretative cross-section through the Rocher de Chabrier and the Forest-Lacour rim syncline. See location of the cross-section in Figure 4.

explain how a fault this size can generate a nearly 500 m offset with only 2 km of lateral extension in map view. The throw represents 25% of the total extend of the fault, which is much larger than the classical 7–10% to be expected (Elliott, 1976). Considering that the Chabrier Liassic section is a vertical megaflap adjacent to a vanished salt structure, this abnormal contact is interpreted as an unconformity (Fig. 11b), associated with the emplacement of the megaflap and the pinching out of the Bathonian and Callovian against it (Fig. 12d). This would explain the successive internal unconformities affecting the

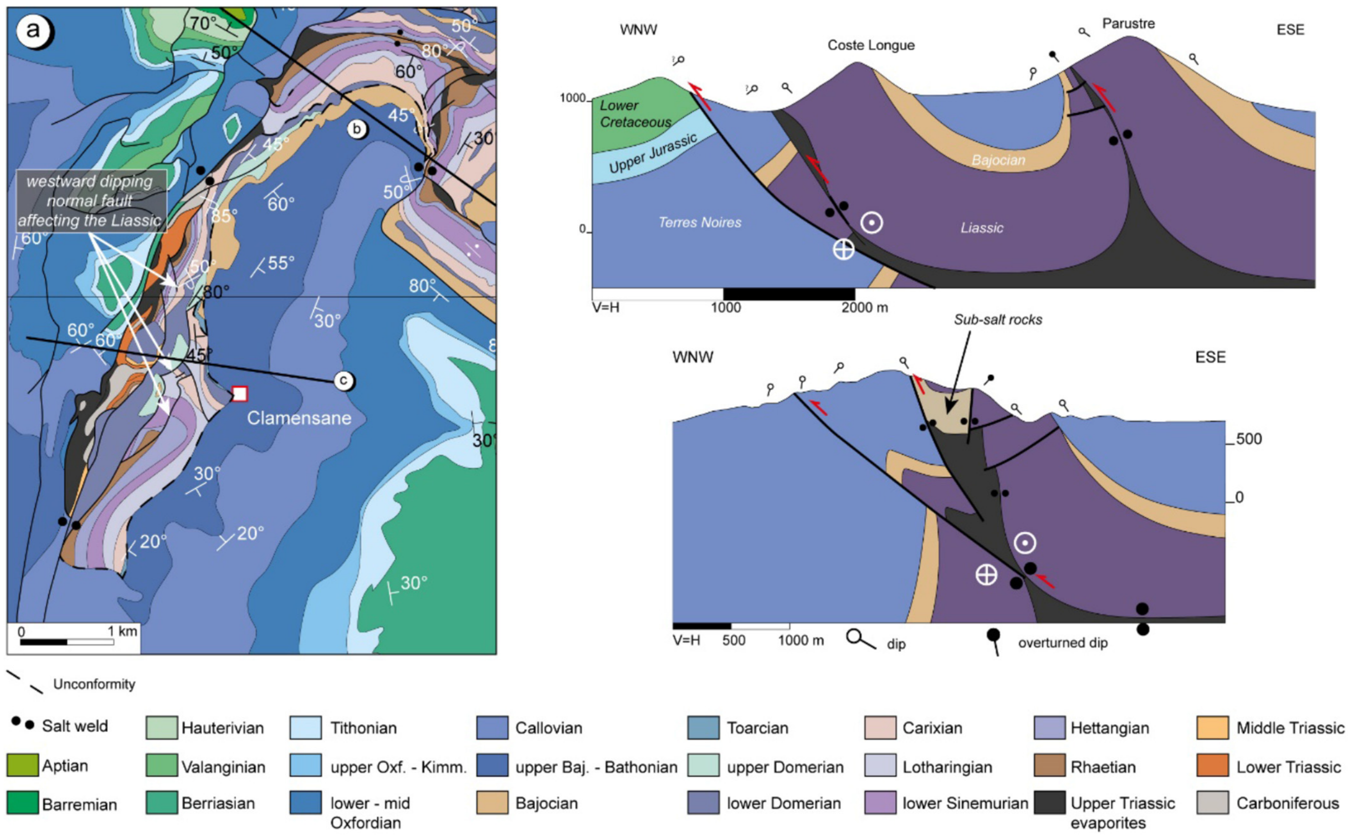

Fig. 13. (a) Interpretative cross-section through the northern part of the Clamensane fault zone (Coste Longue) and the Forest-Lacour rim syncline western termination (Parustre). (b) Interpretative cross-section through the Clamensane fault zone near Clamensane. See location of the cross-sections in Figure 4.

Liassic and the Terres Noires in the adjoining syncline between Coste Longue and the Rocher de Chabrier (Figs. 3 and 4).

We interpret the NE-SW oriented portion of the fault as a tear fault separating the Rocher de Chabrier vertical megaflap from its NW continuation in the southern flank of the Bramefran weld (Fig. 11b).

3.2.2 The Clamensane weld: southwestward continuation of the Astoin diapir

3.2.2.1 *Data and observations*

The Clamensane NNE-SSW fault zone forms the western termination of the Authon–Valavoire thrust sheet and the eastern termination of the Vocontian trough (Fig. 4). It runs NNE-SSW over 10 km, in the northern continuation of the Durance fault and is described as a strike-slip fault acting as a lateral ramp of the Authon–Valavoire thrust sheet (see Gidon, 1997). It is punctuated by several diapiric bodies (Figs. 4 and 13) (Arnaud *et al.*, 1978b). The Clamensane fault zone separates Liassic rocks on the eastern side from Dogger to Lower Cretaceous ones on the western side (Fig. 13a). Both sides are separated by Triassic material that contains blocks of Lower and Middle Triassic together with blocks of Carboniferous (Fig. 13a) (Arnaud *et al.*, 1978a; Gidon and Pairis, 1985). Between Entraix and Châteaufort, the Clamensane fault zone is a sub-vertical scar of gypsum and cargneules blocks within the Terres Noires on each side of the scar (Gidon, 1982) *i.e.* a weld.

The faults affecting the eastern side of the Clamensane fault zone affect mostly the Liassic and are in many places sealed by the Bajocian or the Terres Noires, so they were active during the early history of the Alpine cycle (Fig. 13a) (Gidon, 1982; Gidon *et al.*, 1991a). They are west-dipping normal faults (Fig. 13a) associated with numerous unconformities through the Jurassic. Of these, the best expressed is the unconformity of the Terres Noires (upper Bajocian to mid-Oxfordian) above older deposits, but other local unconformities occur in the Liassic (Fig. 13a).

3.2.2.2 *Interpretation*

The Clamensane fault zone (Figs. 13b and 13c) clearly shows diapiric activity and in therefore interpreted as an imperfectly welded salt ridge (Fig. 13a). The diapiric activity began by reactive diapirism, as suggested by the Liassic normal faults along the apex of the structure (Fig. 13c) before a passive diapir stage during later Jurassic time. The eastern Jurassic section of the Clamensane fault zone is the lateral continuation of the Jurassic Bramefran high to the NE which is the lateral continuation of the Rocher de Chabrier megaflap (Fig. 4). We thus propose that the Clamensane fault zone salt ridge was linked to the Astoin diapir and later used as a lateral

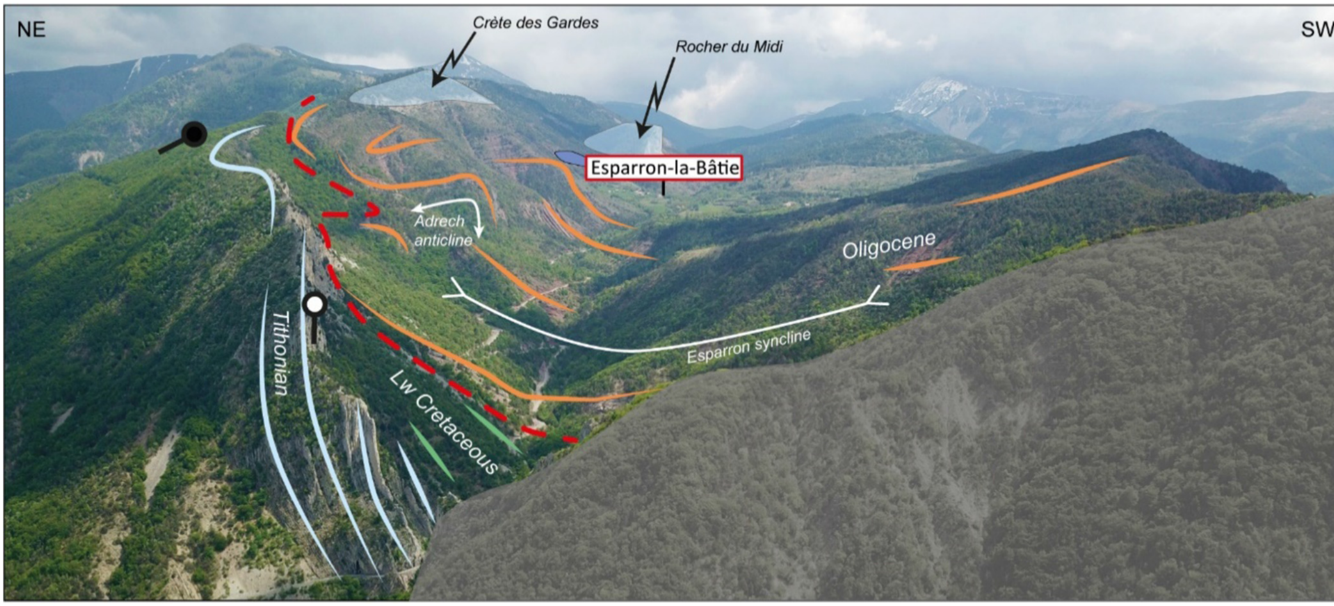

Fig. 14. Interpreted panorama of the Esparron syncline showing the unconformity between the Oligocene and the Tithonian and the Cretaceous underneath it. The Tithonian near the Crête des Gardes must have been vertical during the Oligocene deposition.

ramp of the Authon–Valavoire thrust sheet during Alpine compression.

3.3 The Astoin diapir itself

3.3.1 Eastern zone: a Jurassic advancing salt sheet preserved in an orogen

3.3.1.1 Data and observations

The NW-SE Esparron syncline is cored by Oligocene (Fig. 3) (Arlhac *et al.*, 1983; Gidon, 1997). In details the Esparron structure is formed by two synclines separated by a small anticline called the Adrech anticline (Fig. 14), and the whole structure lies unconformably above an older and much larger syncline containing Tithonian and Lower Cretaceous rocks (Fig. 4) and known as the Reynier syncline (Gidon, 1997). The Digne Nappe truncates the NE flank on the Esparron syncline at the Colle crest (Fig. 14) (Gidon, 1997) and Several small imbricated thrusts have been described between the Esparron syncline and the Digne Nappe at the Gardes crest and Rocher du Midi (Fig. 14). These thrusts limit the Combovin slices which are made of the Terres Noires formation, Tithonian and Middle Triassic (Gidon, 1997). The Oligocene showing growth strata and thickening towards the SW, overlies the Lower Cretaceous and the Tithonian unconformably (Fig. 14). It is nearly vertical on the NE flank of the syncline and overlies the overturned Tithonian towards the NE (Fig. 14). Thus, the Tithonian and the Lower Cretaceous must have been nearly vertical during the deposition of the Oligocene.

The Aubrespin klippe (Fig. 4) is made of overturned Albian marls lying on the Terres Noires of the Turriers basin, just north of the Astoin diapir. It has been described as a klippe originally from the internal Embrunais-Ubaye nappes (Gidon and Pairis, 1986), but the presence of the internal nappes over the Turriers basin has never been proven, and this slice would be their only remnant in the region. We contend that there is a more plausible explanation.

3.3.1.2 Interpretation

The Esparron syncline was previously interpreted as resulting from: (1) pre-Senonian formation of the Reynier syncline, (2) pre-Oligocene erosion, (3) Oligocene deposition, (4) emplacement of the Digne Nappe and the Combovin slices by delamination of the NE flank of the Esparron syncline (Gidon, 1997). The pre-Senonian compressional phase of the Dévoluy, which has been extrapolated to the whole SW French Alps is no longer considered as a compressional event but rather as a Cretaceous gravity gliding event in the Vocontian trough (Michard *et al.*, 2010).

We have shown that the Astoin diapir created an overturned flap towards the south and reached the seafloor during the deposition of the Terres Noires (Fig. 15) (Célini *et al.*, 2020). The diapir must have been very large in the light of its map extension and the size of the rafts it has deposited on the seafloor (see Célini *et al.*, 2020). Such a diapir could have generated an important salt sheet on the Callovian-Oxfordian seafloor. Along the road from Bayons to Astoin, the Dogger strata show no deformation and form a south dipping monocline (Fig. 15) as far as the overturned Tithonian section of the Esparron syncline (Fig. 14). The contact between the allochthonous evaporites and the raft is climbing upward into the Terres Noires stratigraphy (Fig. 15). It looks like a thrust ramp but it cannot be because the allochthonous body was deposited here during the Jurassic (Célini *et al.*, 2020).

We propose that after the salt became allochthonous with the formation of the Astoin overturned megaflap (Fig. 15b), an advancing allochthonous salt sheet developed at the seafloor (Fig. 16). The thrust-like contact between the allochthonous

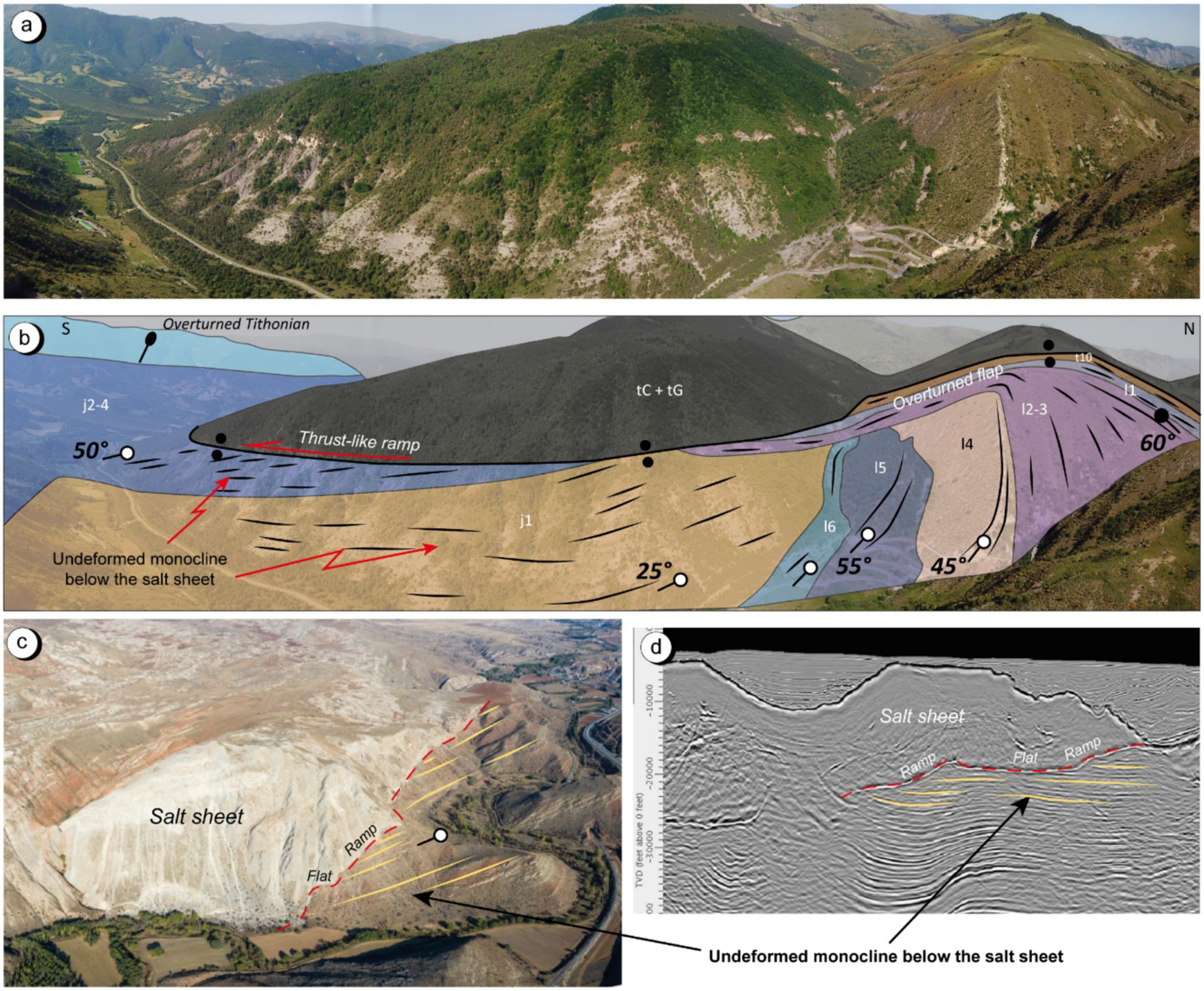

Fig. 15. (a) and (b) Uninterpreted and interpreted panoramas of the Astoin megaflap and its southern continuation which forms an allochthonous salt sheet during the Jurassic. (c) Anolague onshore salt sheet in the Sivas Basin in Turkey (picture from JC Ringenbach). (d) Analogue offshore salt sheet in seismic line in the Gulf of Mexico. The Astoin allochthonous salt sheet ((a) and (b)) presents the same features of salt sheets ((c) and (d)) which are: a contact which climbs upward into the stratigraphy between the allochthonous salt and its substratum and the undeformed monocline of the substratum below the salt sheet.

material and the Terres Noires must reflect the “ramps” and “flats” at the base of the advancing salt sheet as it climbed through the accumulating sedimentary section of the Terres Noires (Fig. 15c). Such salt related structures have been described from offshore seismic in many places in the world (*e.g.* the Gulf of Mexico, Fig. 15d) and in orogens as in the Sivas basin in Turkey (Fig. 15c) (Hudec and Jackson, 2006; Legeay *et al.*, 2019). We assume that the allochthonous salt sheet overflowed towards the south and was accompanied by the folding and overturning of the Tithonian and the Lower Cretaceous of the Reynier syncline. As well as its advance towards the south, the diapir must have also overflowed northwards, something misinterpreted by earlier authors as thrusting northward on the Turriers basin through the Sagnes fault.

The Aubrespin klippe probably also betrays the presence of the salt sheet. We propose that the allochthonous salt sheet was first covered by Albian marls (Fig. 16). Later during the deflation or erosion of the salt sheet, a piece of the roof of the salt sheet sunk into the salt, was overturned and deposited onto the Terres Noires of the Turriers basin underneath the deflating salt sheet (Fig. 16). Following the same idea, the Le Cerveau allochthonous body, made up of Liassic and Bajocian beds, which has been described above as the carapace of the Astoin diapir truncated by the Digne Nappe, can also be regarded as a part of the allochthonous salt sheet carapace that was deposited here during its deflation or erosion (Gidon, 1997).

This interpretation is consistent with a number of observations. First, the formation of the Astoin diapir during

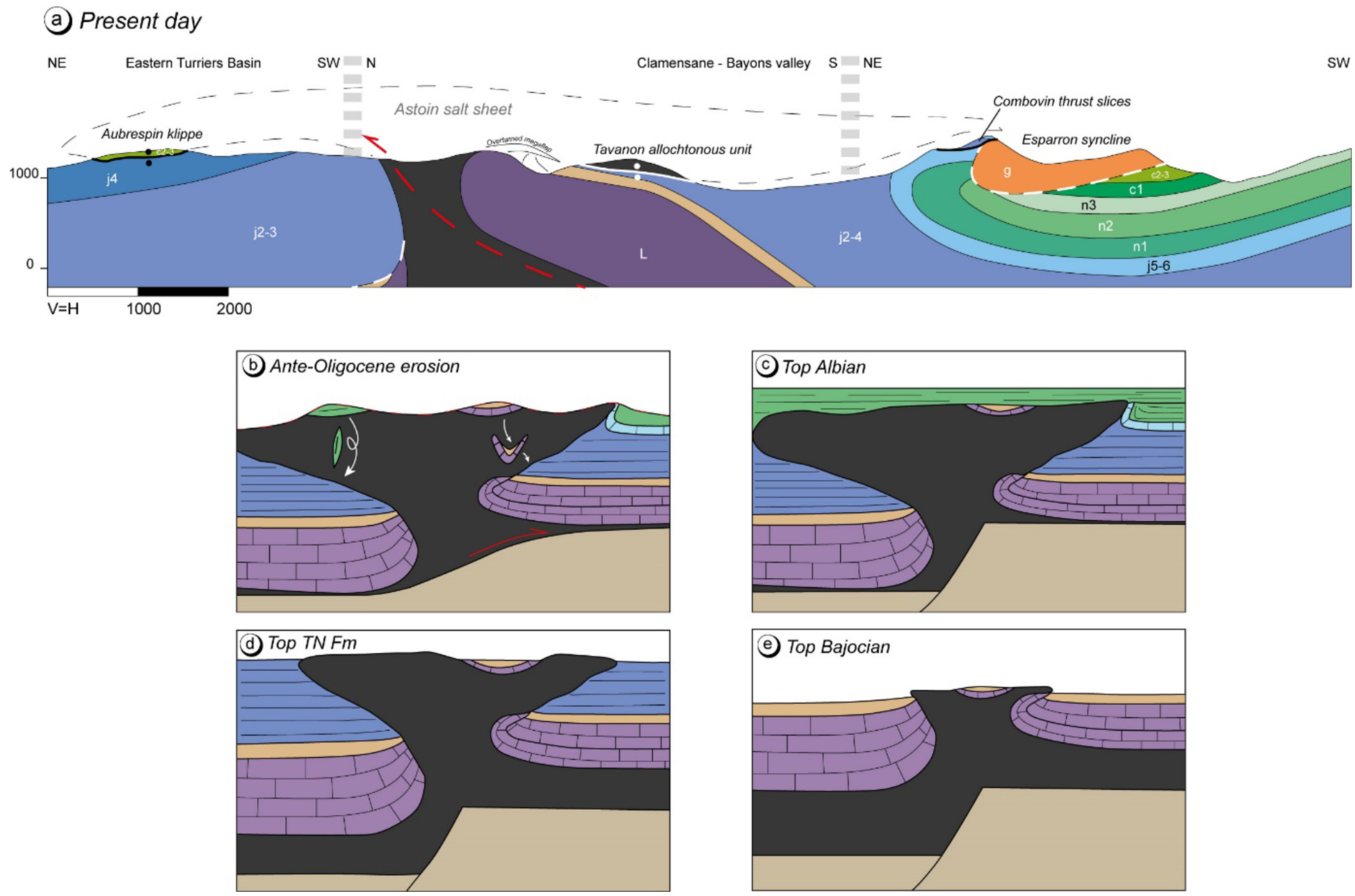

Fig. 16. Present-day interpretative cross-section illustrating the Astoin allochthonous salt sheet inherited from the passive margin stage preserved into an orogen. See location of the cross-section in Figure 4. (b), (c), (d) and (e) are simplified sketches illustrating the emplacement of the allochthonous salt sheet.

the Liassic and its arrival at seafloor during the Dogger was responsible for the development of an overturned flap of Liassic covered by allochthonous salt. Second, the thrust-like ramp contact between the Terres Noires and the allochthonous salt sheet records its advance. Third, the very low intensity of deformation of the Terres Noires below the salt sheet can be seen in many other places (*e.g.* Kergaravat *et al.*, 2017). We consider that the overturned klippe of Albian marls above the Terres Noires of the Turriers basin is a remnant raft of the dismantled carapace of the submarine salt sheet.

The Astoin allochthonous salt sheet can therefore be thought as an example of an advancing salt sheet in a passive margin setting still preserved in spite of later orogenic deformation.

3.3.2 Western zone: the Picouse–Valentin sector

3.3.2.1 Data and observations

This sector, located just west of the Astoin diapir (Figs. 3 and 7a), exposes three vertical contacts that have been described as post-Oligocene thrusts faults steepened by later folding (Arnaud *et al.*, 1977). Upper Triassic evaporites occur near these vertical contacts (Bramefran, Bouchères, Bois Lardat weld and Casses welds) and the Liassic section is very reduced and, like the Turriers Liassic section, contains many sedimentary gaps (Fig. 7a).

In several locations, the Liassic section is affected by normal faults. These are sealed at different stratigraphic levels in different localities – at the top Liassic (near the Bramefran high), the top Bajocian (at the Eyrolle crest) and within the Terres Noires (near Bouchères). The faults affect mostly the Hettangian to Carixian strata, and are always located near an evaporite outcrop or a vertical contact (Fig. 7). On the northern side of the Bramefran high, the Carixian pinches out between the Sinemurian (overturned 80° to the SW) and the Domerian which dips 50° to the NE, with the Carixian missing (Fig. 17). This means that the Sinemurian was dipping around 50° to the NE when the Domerian was deposited. Apart from a few locations where the Toarcian is present, the Bajocian always lies unconformably above various stages of the Liassic. The Terres Noires formation also lies unconformably above all older strata (Fig. 7a). On the Patassiers high (Figs. 7 and 8a), the Callovian part of the Terres Noires formation directly lies over the Hettangian. In the Picouse–Valentin sector, as in the Turriers basin farther north, several olistoliths of Liassic occur within the Terres Noires formation and Lower Triassic, Middle Triassic, and Liassic olistoliths rest on the Upper Triassic evaporites. Gidon and Pairis (1986) recognised that these

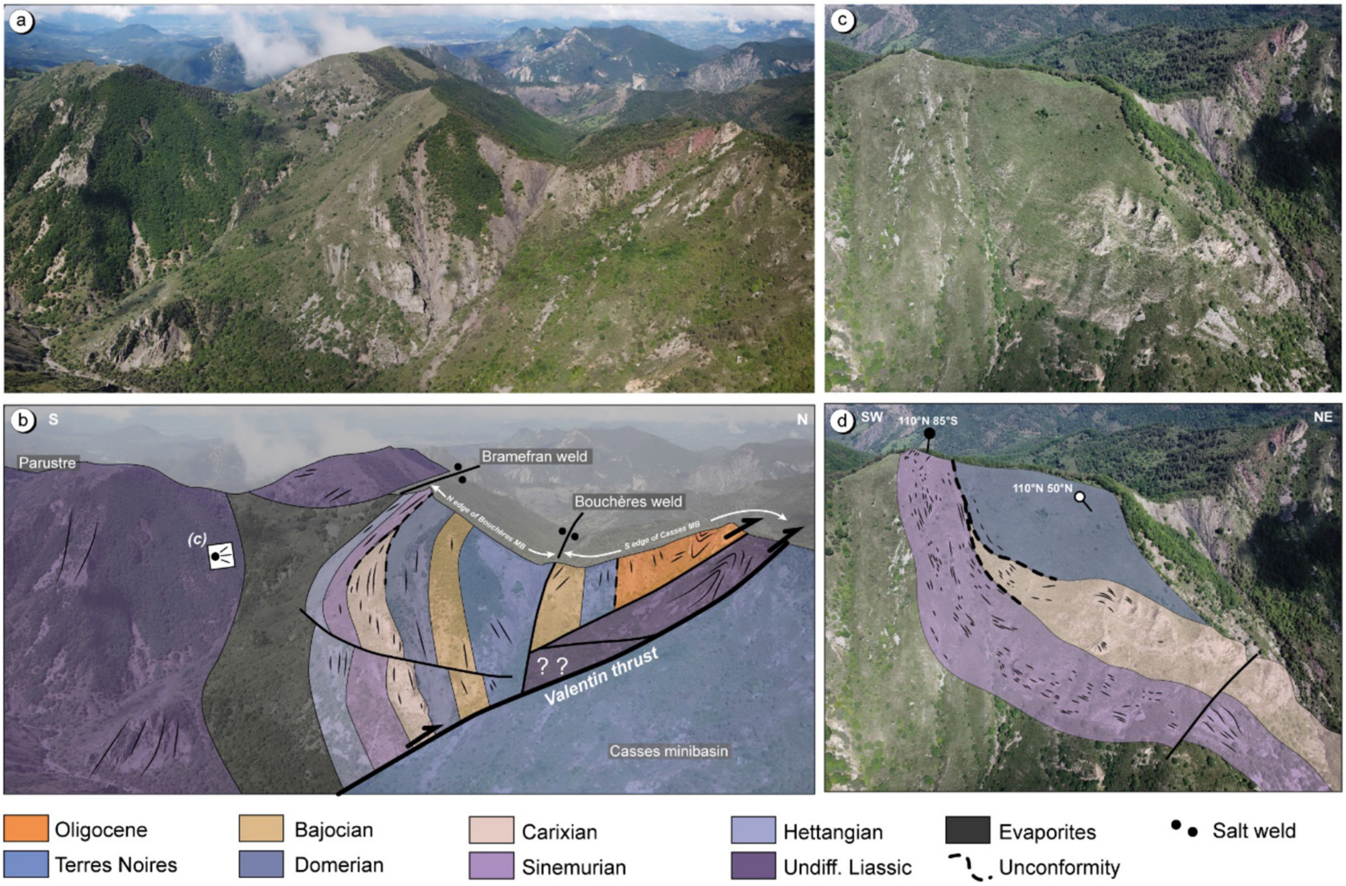

Fig. 17. (a) and (b) Uninterpreted and interpreted panorama of the Bramefran and Valentin highs, showing the Valentin thrust cutting through the Bouchères weld. (c) and (d) Uninterpreted and interpreted pictures of the pinch out of the Carixian near the Bramefran weld, see location of the picture on (b).

olistoliths were emplaced during the sedimentation of the Terres Noires formation in the Turriers basin (Gidon and Pairis, 1986), but in the Picouse–Valentin sector they have been thought to be associated with Alpine shortening (Arnaud *et al.*, 1977). Between the Terres Noires formation and the Eocene, no rocks have been preserved in the area. To the north, the Terres Noires formation is thrusted over the Oligocene. Two thrusts, the Pierre Pouillouse thrust towards the NNW, and another structure further SSW intersect just north of the Patassiers high. These thrusts are parts of the Faucon thrust slices which Ehtechamzadeh Afchar and Gidon (1973) described as having northwesterly vergence (Ehtechamzadeh Afchar and Gidon, 1973).

3.3.2.2 Interpretation

The Picouse–Valentin sector lies at the boundary between two 1/50 000 geological maps (Laragne and Seyne). The interpretation is completely different on both geological maps (Arlhac *et al.*, 1983; Gidon *et al.*, 1991a). Historically the interpretation has been a succession of imbricated thrusts with contrasted vergences but we propose that because the vertical contacts are located adjacent to the successive unconformities and redeposited olistoliths, they are welds resulting from the squeezing of Jurassic salt structures during the Alpine compression (Fig. 7b).

It follows that the successive unconformities represent large ("mega") halokinetic sequences and the olistoliths pieces of the carapace of the diapir. The normal faults affecting the Liassic section, sealed during the Dogger, are interpreted as the consequence of reactive diapirism (Jackson and Vendeville, 1994; Dooley *et al.*, 2005; Tavani and Granado, 2014). Some of the small sedimentary packages located between the welds are interpreted as the remnants of the carapace of the Astoin diapiric complex, which has been dismantled and rafted during the rise of the Astoin salt sheet, thus explaining the present-day structural complexity.

The larger depocenters located between welds are interpreted as small scale minibasins that developed at the roof of the Astoin diapiric complex during the Jurassic (Fig. 7b). Indeed, the edges of those depocenters show the classical features of minibasin edges such as successive unconformities and apparent thinning against welds.

The present-day structural layout of this sector shows variations from east to west (Fig. 18). In the east near the main extrusion zone of the Astoin diapir, there is only one salt structure where pieces of Liassic diapir carapace are visible namely the Picouse crest (Fig. 18a) and the Grande Gautière

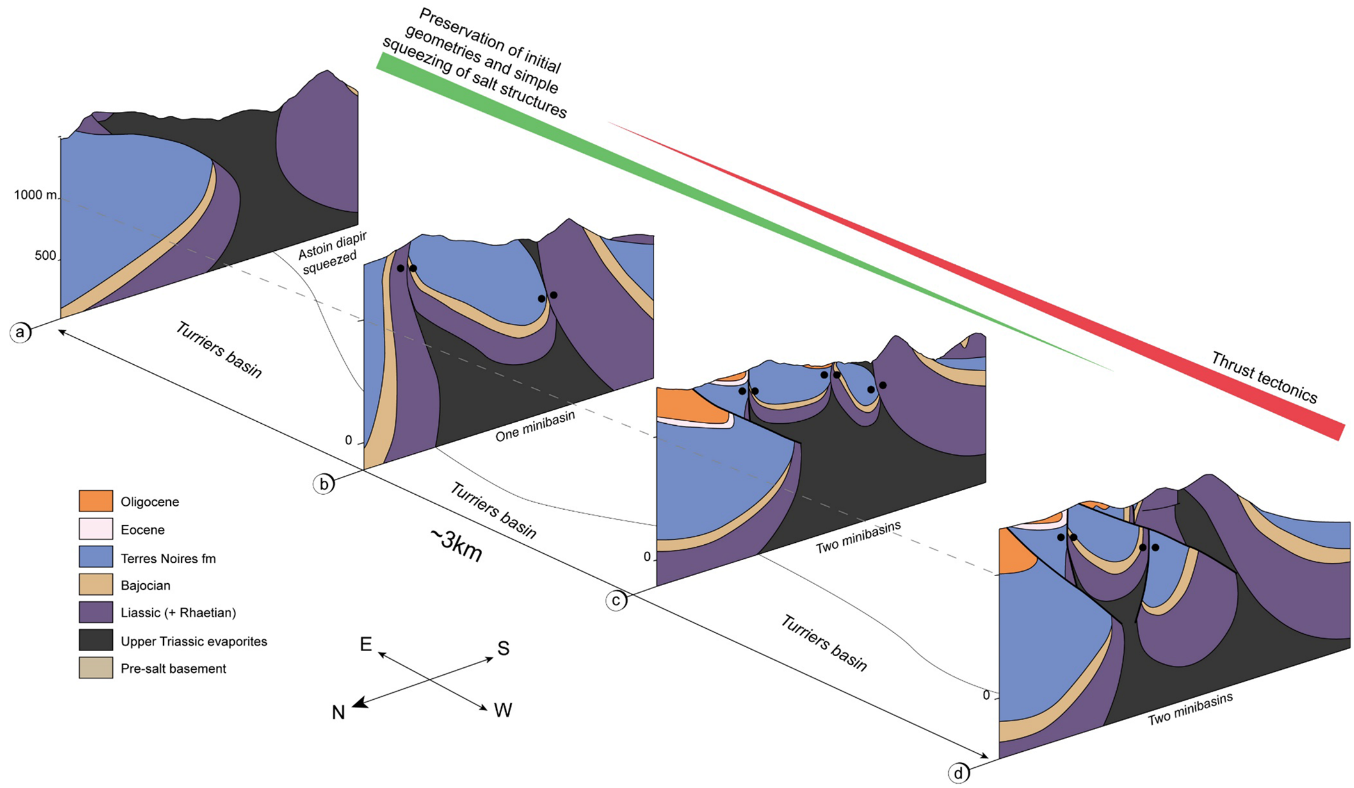

Fig. 18. Serial interpretative cross-sections through the Picouse–Valentin sector. See locations of cross-sections in Figure 7b.

(Fig. 7a). In the west, the Bois Lardat, the Casses, the Bouchères and the Bramefran welds separate three minibasins in the Picouse–Valentin sector (Figs. 7 and 18). The Bois Lardat weld is the eastern continuation of the Le Caire salt wall. The Casses weld comprises NNW-SSE and WNW-ESE segments (Fig. 7b), separating the Gautière minibasin from the Casses minibasin. We propose that the Bouchères weld was originally continuous with the Vermeil anticline which eastwards becomes the Bouchères salt wall, and is truncated by the Valentin fault (Fig. 7b). The supposed klippe delineated by the Valentin fault and the Bouchères weld (Fig. 7b) is actually the NE flank of the Bouchères salt wall (the SW edge of the Casses minibasin) which has been shortcut and transported towards the north by the Valentin fault together with the Bramefran weld located just to the south. This implies that the major part of the Bouchères minibasin (located between the Bouchères salt wall and the Bramefran salt wall) is now located beneath the Bramefran weld and the Graves salt expulsion basin that is thrusting over the Bouchères minibasin towards the north (Fig. 18d).

4 Discussion

4.1 Time-step evolution of the diapiric complex

We propose a schematic (not to scale) time-step reconstruction for four serial cross-sections through the Picouse–Valentin sector (Fig. 18) with four main steps before present-day that are (1) the Liassic during which the diapirism is initiated, (2) the Dogger during which salt extrudes onto the seafloor, (3) the Oligocene during which salt tectonics is still active and (4) the Miocene shortening event (Fig. 19).

4.1.1 Liassic initiation of diapirism

We assume that similarly to other locations in the southwestern branch of the Alpine arc and more especially the Digne Nappe area, the Liassic rifting triggered salt tectonics (Graciansky *et al.*, 1986; Mascle *et al.*, 1986; Dardeau and Graciansky, 1990; Dardeau *et al.*, 1990; Graham *et al.*, 2012, 2019). The normal faults near the Bouchères weld, the Bramefran weld and at the Eyrolle crest must reflect the faulting of the supra-salt layers in response to the rifting initiating the rise of salt, along ridges (Fig. 19 – 4). Not all the Liassic sections located near salt structures or welds show faulting (Fig. 19 – 4). In the east, near Astoin, the Liassic section is not affected by normal faulting and the diapiric activity seems to be mostly controlled by the sediment load, building a megaflap (Célini *et al.*, 2020). At the Patassiers high or on both sides of the Casses weld, the Liassic section is not affected by normal faulting, but the numerous successive unconformities observable in map view (Fig. 7a), can be interpreted as resulting from passive diapirism. As proposed by Célini *et al.* (2020) for the Digne Nappe area, we propose that in the Picouse–Valentin sector, reactive and passive diapirism were coeval during the Liassic.

The presence of the "Turriers-type" Liassic section in the Picouse–Valentin sector is, due to its presence near the crest of a salt structure and not to the fact that it is the Liassic from the autochtonous units (Célini *et al.*, 2020).

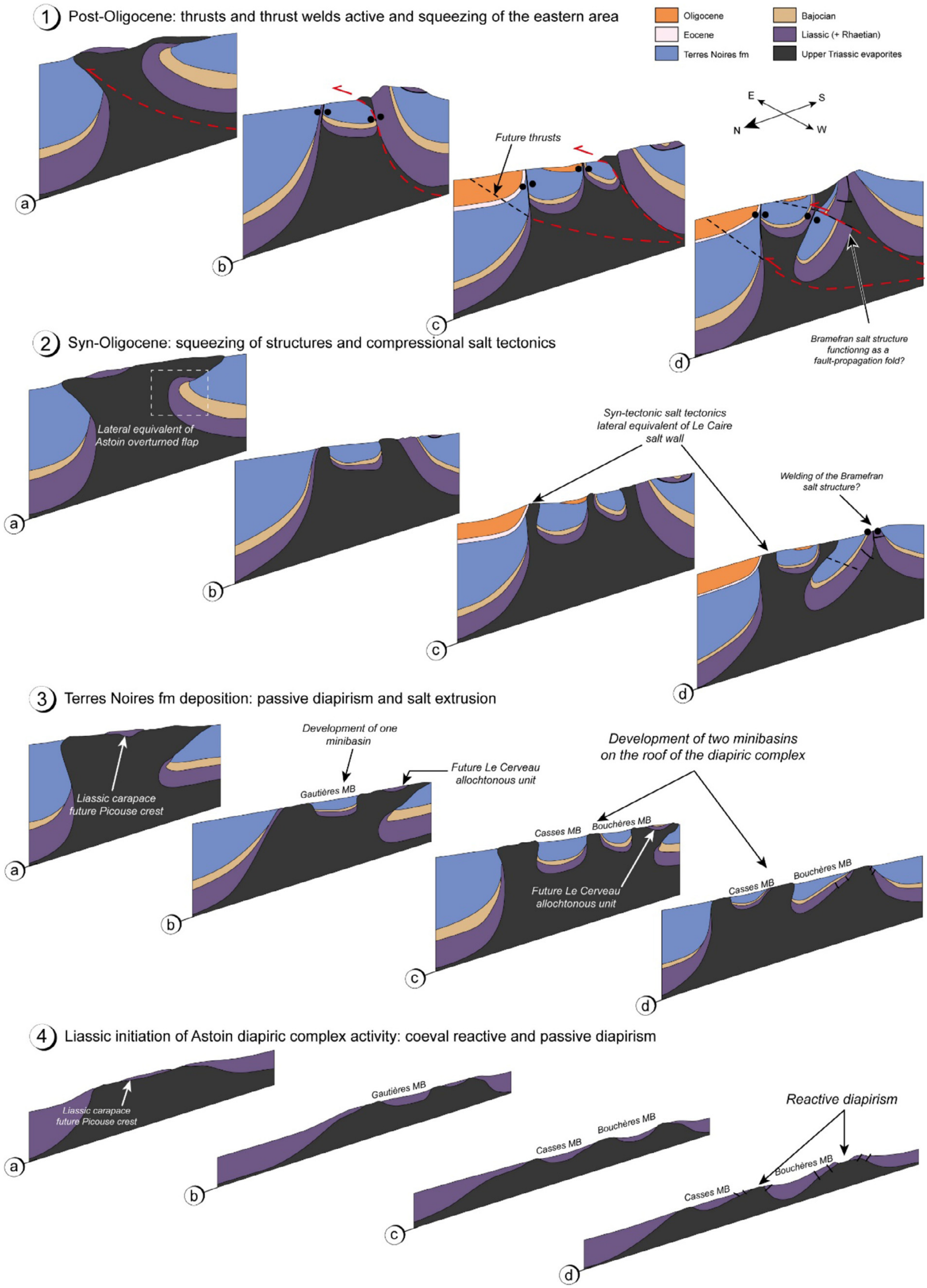

Fig. 19. Time step reconstruction of the cross-sections through the Picouse–Valentin sector, present-day cross-sections in Figure 18.

4.1.2 Allochtonous salt and passive diapirism during the Dogger

During the Dogger, all the salt structures grew passively. The absence of normal faults that are sealed during the lower Dogger, and the successive unconformities observed near the various welds (Fig. 7a) argue for the passive growth of diapirs. To the east, the Astoin diapir extruded at the seafloor during the Bajocian (Célini *et al.*, 2020), and emplaced an advancing allochthonous salt sheet forming a ramp into the Terres Noires and affecting the Mesozoic until at least the Lower Cretaceous (Fig. 16). In the Picouse–Valentin sector, the Bajocian and Liassic olistoliths show extrusion of salt at the seafloor during the deposition of the Terres Noires (Fig. 19-3) with the inclusions of olistoliths as in the Turriers basin to the north (Gidon and Pairis, 1986).

4.1.3 Oligocene salt tectonics and compression

A key point is that salt tectonics was active during the Oligocene at several locations such as at Saint-Barthélémy (Fig. 9) and at the Le Caire salt wall (Fig. 10). The lateral continuity of the Le Caire salt wall, which forms the Bois Lardat weld (Fig. 7), was an active diapir during the Oligocene, resulting in a halokinetic fold within the Eocene–Oligocene beds of the La Cassine syncline (Fig. 19-2). These observations testify that several salt structures must have been active during the entire Mesozoic and during the lower Tertiary, before the final reactivation during shortening. However, it is difficult to decipher whether salt tectonics was continuous during the whole Alpine history of it there were stops of activity and reactivation due to tectonic strains. In the area, the important gap between the Malm and the Eocene–Oligocene deposits makes difficult to know what happened during that period. In a few locations in the Alps such as in the Diois–Baronnies domain, salt diapirs seems to have been continuously in activity (Dardeau *et al.*, 1990). Following this model, the hypothesis of a continuous salt activity can be done for the Astoin area during the whole Alpine history. On the other hand, the transition between Eocene and Oligocene corresponds to an extensional event related to subduction of the southern Ligurian Tethys ocean to the south of the area (Séranne *et al.*, 1995; Lacombe and Jolivet, 2005; Handy *et al.*, 2010). If we consider the hypothesis of a stop in salt activity, this extensional event can reactivate salt flow at that time. Without strong evidence for one hypothesis or the other, but taking into account the important sedimentary gap between the Malm and the Eocene–Oligocene, we suggest that salt activity might have stopped. An important erosion phase occurred prior to the Eocene–Oligocene, and the extensional event of that period reactivated salt flow resulting in halokinetic deformation of Eocene–Oligocene rocks in a few locations.

The thrusts are post-Oligocene in age. We propose that during the Oligocene, Alpine compression was squeezing the salt structures, enhancing compressional salt tectonics, and progressively creating all the welds (Fig. 19-2). Shortening was taken up by the salt and only the surrounding depocenters are now preserved.

4.1.4 Lateral variation of the diapiric complex crushing during main Alpine events

The main compressional event occurred after the Oligocene. At the larger scale, the whole southern edge of the Astoin diapir (*i.e.* the Clamensane–Bayons basin, Fig. 4) is slightly transported towards the north over a hinterland-ward thrust (Fig. 1b). Looking more in details, the compression of the whole structure varies laterally. In the east, where the Astoin diapir was the larger it was still squeezed while in the west, where salt has been welded out, thrust tectonics affected the minibasins (Fig. 19-1), with thrusts accommodating the shortening (*e.g.* the Valentin and the Pierre Pouillouse thrusts, Fig. 7b). The Pierre Pouillouse thrust truncates the southern border of the Turriers basin in sections (c) and (d) while the Valentin thrust cuts through the Bouchères and the Casses minibasins only in the cross-section (d) (Fig. 19).

Laterally the Astoin diapiric complex has recorded the Alpine compressional events in various ways (Fig. 18). The eastern and the western parts of the diapiric complex evolved differently (Fig. 19). The eastern part allowed the development of allochthonous salt from the Bajocian until at least the Albian (Fig. 16). Later, that part of the diapir has been squeezed and the southern edge of the diapir, acting as a backthrust, has been thrusted over the northern edge (Fig. 18). In the western part salt activity has developed minibasins at the roof of the diapiric complex witnessed by several residual welds (Figs. 7 and 18). These welds themselves are recording shortening through squeezing, and could have possibly been activated as thrusts by Alpine compression. Minor thrusts have shortcut some of these welds giving the impression of numerous imbricated thrusts in map view (Fig. 3).

Minibasins at the top of the diapiric complex are now located between sub-vertical welds and some of them have their borders truncated by thrust faults (Fig. 18). Alpine shortening has rotated the Bouchères minibasin which is apparently overthrusted by the Casses minibasin (Fig. 18). The Valentin fault has cut the southern flanks of both minibasins. Rotation of minibasins resulting from shortening has been recorded in other areas notably the Sivas Basin in Turkey (Kergaravat *et al.*, 2016).

4.2 Network of salt structures or a structure functioning as a network?

In map view, when all the salt structures and the associated basins are restored to their original locations in the Jurassic with respect to the Astoin main diapir main (Fig. 20), we see the main feeder of the diapiric complex in the east (Fig. 20), and an allochtonous salt sheet emplaced during the passive margin stage (Fig. 16). Reconstruction is impossible east of the main feeder, because the area has been transported by the Digne Nappe (Fig. 4). In the west of the main feeder, the salt structures seem to have been connected all together in a network forming fingers (Fig. 20). Some structures of the Astoin diapiric complex present a few orientations (Fig. 20) that are not the ones of the extensional basement cutting faults resulting from the Liassic rifting which are NW-SE and

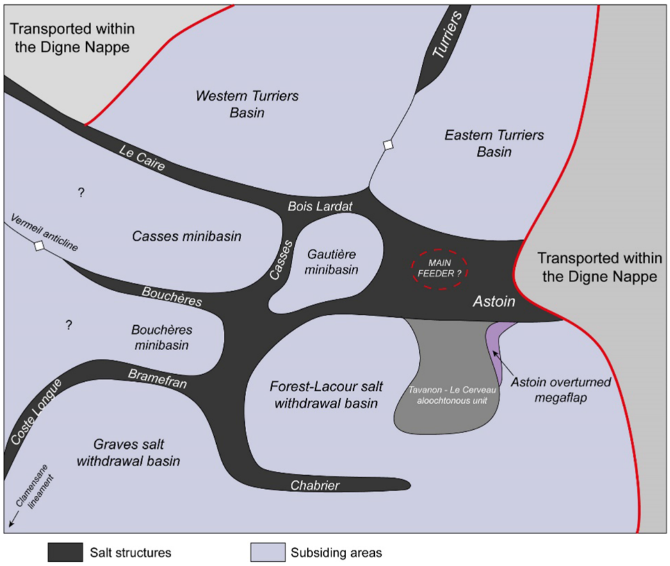

Fig. 20. Map view of the Astoin diapiric complex with the salt structures and the associated rim synclines in their palinspastic position during the Jurassic. The schema is not to scale and its aim is to locate the different structures in their original position.

NNE-SSW (Barféty *et al.*, 1979; Lemoine *et al.*, 1989). We suggest that the coeval passive and reactive diapirism in the sub-Alpine chains during the Liassic allowed the development of structures aligned with extensional structures in the sub-salt basement as well as salt structures with more or less random orientations (Fig. 20).

Unlike other diapirs observed in nature, the Astoin diapiric complex does not show clear circular (or near circular) boundary but seems to be a huge diapir with radial salt ridges connected to it. The spatial organisation of the Astoin diapiric complex in salt welds separating minibasins (Figs. 4, 7 and 20) seems to be similar to networks of salt structures (diapirs connected by salt walls and minibasins between the salt structures) that have been described onshore in the Flinders Ranges in Australia or offshore in the North Sea (*e.g.* Rowan and Vendeville, 2006). A salt province functioning as a network of salt structures (diapirs at the junction of salt walls) and minibasins between them has also been reproduced by physical modelling with sandbox and silicone (Rowan and Vendeville, 2006). A scale problem remains because the networks observed in nature run over tens of kilometres, while the physical models show networks over tens of centimetres. The Astoin diapiric complex illustrates such an organisation over a few kilometres only and sometimes over a few hundreds of meters, which makes it unique (see Fig. 4).

4.3 Old rocks but recent and evolving ideas

Salt structures have been recognised around the world since the 1850's (see Ville (1859) in Jackson and Hudec, 2017). In the Southwestern French Alps, the first diapiric structures were identified during the 1940's within the Baronnies area (Vocontian Trough): the Suzette and Propiac diapirs (Lapparent, 1940). In 1939, Jean Goguel already described Triassic extravasations ("*extravasions triasiques*", *i.e.* a diapiric salt body) for the Astoin diapir (Goguel, 1939). Later, the Astoin diapirism was considered as minor with respect to the Alpine shortening (*e.g.* Arnaud *et al.*, 1977). At that time, the emphasis in structural geology was on fold and thrust tectonics in places like the Southwestern French Alps and Pyrenees (Saura *et al.*, 2015). Salt in the southern Subalpine Chains was considered for decades only as an efficient décollement level for thrusts (Faucher *et al.*, 1988; Fry, 1989; Lickorish and Ford, 1998; Apps *et al.*, 2004; Ford *et al.*, 2006), following the new wave of thrust tectonics coming from the US rockies and developing cross-section balancing techniques (Dahlstrom, 1969; Elliott, 1976; Boyer and Elliott, 1982; Davis *et al.*, 1983; Mitra and Boyer, 1986, non-exhaustive list). We see now that this is only applicable where the salt is not involved in early pre-thrusting salt tectonics which can influence the later compression as in the Jura fold-and-thrust belt (Philippe *et al.*, 1998; Sommaruga, 1999).

In the meantime, since the 1980's, rare outsiders were trying to integrate the role of salt, and particularly the strong structural inheritance and involvement of salt rock in the Alpine compression in the Maritimes Alps, the Vocontian Trough or the Embrunais–Ubaye thrust sheets (Graciansky *et al.*, 1986; Dardeau and Graciansky, 1990; Dardeau *et al.*, 1990). These authors proposed that diapiric structures were emplaced during the Liassic, then squeezed during the compression. In order to bridge the gap, those authors also proposed that thrusts were able to go through or nucleate into those salt structures.

More or less the same is true for our study which integrates the salt tectonics concepts developed since the mid 1990's. The area surrounding the Astoin diapir and more precisely the Picouse–Valentin sector and the Turriers basin, have been interpreted as the result of many imbricated thrusts that are themselves folded by later shortening events (Ehtechamzadeh Afchar and Gidon, 1973, 1974; Arnaud *et al.*, 1977). Those interpretations lead to a complex polyphased structural history with many different shortening events and directions that are sometimes the opposite or very oblique to the regional shortening direction (*e.g.* Ehtechamzadeh Afchar and Gidon, 1973).

It is only recently that work on the Barre de Chine near Barles that has pointed out and described with modern concepts the involvement of an early salt tectonics and its structural inheritance in the Alpine history (Graham *et al.*, 2012). In addition, our work in the Digne Nappe area revealed many early salt structures and shows the importance of the early development of salt structures in the subsequent history (Célini *et al.*, 2020). Salt can no longer be considered only as an efficient décollement level. Our interpretation proposes a more straightforward way to interpret the anomalous contacts observed within the Jurassic sections of the area of the Astoin diapir (Fig. 3). The rheology of salt allows both hinterland and foreland verging structures, and is more elegant explanations than involving many shortening events with very different shortening directions.

5 Conclusion

The study of the Astoin diapir reveals that it formed a plurikilometric diapiric complex (with several structural domains) where the Astoin diapir constituted the main diapir to which are connected several salt ridges. As the other salt-controlled structures in the sub-Alpine chains (Dardeau and Graciansky, 1990; Graham *et al.*, 2012; Célini *et al.*, 2020; Graham and Csicsek, 2020), the diapir started to develop during the Liassic by both reactive diapirism, triggered by the Liassic Tethyan rifting, and passive diapirism (Célini *et al.*, 2020). During the post-rift stage of the Alpine cycle, all the structures grew passively. In the eastern part of the diapiric complex, an allochthonous salt sheet developed that was buried during the Albian, while in its western part, Jurassic filled minibasins developed on top of the inflating diapir. These minibasins were separated by salt structures organised as a network. A few locations evidence Oligocene salt tectonics of which the extensional event of the Eocene–Oligocene transition might have been the trigger. The area of the Astoin diapiric complex has been strongly pre-structured by salt tectonics resulting in an important structural inheritance that highly impacted further compression. Major Alpine compressional events, that occurred after the Oligocene, created welds and thrust weds, amplified already existing structures and sometimes created compressional features that crosscut inherited salt-related structures. The Astoin diapiric complex shows the important structural inheritance of pre-existing salt-controlled structures within an orogenic wedge as well as the huge lateral variability in the record of salt activity.

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