Triassic evaporites and the structural architecture of the External Hellenides and Albanides (SE Europe): Controls on the petroleum and geoenergy systems of Greece and Albania

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Abstract

A combination of well data, seismic information on thrusting and tectonic shortening, plus analyses of the nature and depth of the Mesozoic units related to main detachment horizons (Triassic evaporites, flysch), are used to review and further update the complex structural styles of the External Hellenides and Albanides Orogenic Belts, SE Europe. In the study area, the late Alpine orogenic evolution resulted in a structural architecture characterised by the successive thrusting westwards of tectonic nappes (Gavrovo/Kruja, Ionian), with an imbricate tectonic style prevailing in all external zones. In the internal and central Ionian zone, imbricate and duplex structures are recorded, especially where about 24 km of stacked Mesozoic-Tertiary successions have been formed in Albania. Triassic evaporites, up to 3.5 km thick, acted as a detachment horizon for the internal deformation of the Ionian and Pre-Apulia zones (1.7-1.8 km thick in Greece), whereas the Miocene flysch unit contributed to the deformation of the Ionian zone. In the Ionian zone, Triassic evaporites are laterally continuous and act as an effective seal unit when thrusted above Mesozoic carbonate/Tertiary units. Most of the oil and gas fields, oil shows and surface seeps have been developed in association with the relative more complex structure styles in the internal and the central Ionian zone of Albania and Greece. The Triassic evaporite detachment is detected at depths of 8 km to 22 km in Albania, and about 5 km to 12-13 km in Greece). The above mentioned structure styles were later affected by strike-slip tectonics and extensional deformation active since the Early Pliocene times. We propose that hydrocarbon migration primarily followed developed thrust faults and important halokinesis, to charge fractured Cretaceous-Eocene carbonate reservoirs in the overthrust unit (Ionian zone), likely beneath the thrusted anticlinal belts. These sub-thrust structural models are related to the evaporites. Sub-thrust plays, referred to the autochthonous units (Apulia, Pre-Apulia/Paxos, Sazani zones), may also present reservoir potential in Albania and Western Greece. Upper Miocene and Pliocene deposits (sands) record reservoir potential in stratigraphic traps and good caprock characteristics in the Peri-Adriatic depression (Albania), whereas Messinian evaporites and clays may document seal potential for Upper Miocene sands and in the southern areas of the Ionian Sea (Kyparissiakos gulf, SW Kythira).

Keywords: SE Europe; structural architecture, halokinesis; evolutionary model; petroleum systems; hydrocarbons migration; geoenergy.

1. Introduction

Structural analyses of sedimentary basins are key to petroleum geoscience as sub-surface structures of various kinds contribute to hydrocarbon migration and trapping (Gussow, 1954; Roof and Rutherford, 1958; Hobson, 1962; Harms, 1966; Cartmill, 1976; Warren, 2000, 2006). Structural elements such as trap-door blocks, en echelon structures, thrust related anticlines, acting together with time-dependent changes in local structural trends, promote the migration of fluid and heat (Vilasi et al., 2006; Vilasi et al., 2009; Roure et al., 2010) not only in sedimentary basins, but also throughout the upper crust (Mandl and Harkness, 1987; Jones et al., 1998; Aydin, 2000; Warren, 2000, 2006). This is particular the case of evaporite-rich provinces of the Alpine Orogenic Belt, such as Western Greece and Albania, in which Triassic salt units can decouple deformation above and below to mask potential hydrocarbon and geothermal prospects at depth (Kokinou et al., 2005; Velaj, 2015; this work).

The complex geological structure of the Hellenides and Albanides branches of the Alpine Orogenic Belt (Sage and Letouzey, 1990; Chaumillon et al., 1996; Sotiropoulos et al., 2003; Marnelis et al., 2007) has so far caused serious obstacles to explaining their Mesozoic and Permian-Triassic evolution (see Fig. 2 in Kokinou et al., 2005). Nevertheless, new geological and structural models have supported the presence of petroleum and geoenergy systems in Permian-Triassic salt and its underlying Paleozoic rocks (Kamberis et al., 1996; Velaj, 2001; Zelilidis et al., 2003; Roure et al., 2004; Kokinou et al., 2005; Karakitsios and Rigakis, 2007; Karakitsios, 2013; Velaj, 2015). In the absence of high-quality geophysical and seismic data, most of which reveal limited penetration depths and complex artifacts due to the inherent structural complexity of Albania and Western Greece, regional transects and structural interpretations based on well and outcrop data have been crucial to the recognition of petroleum-bearing regions and putative paths for fluid and heat in both countries. For instance, hydrocarbon exploration based on such transects has resulted in the discovery of the Prinos

Field in 1971, located south of Kavala (Eastern Greece), and the marginally economic Katakolon Field of Western Greece in 1981 (Xenopoulos, 2000; Kamberis et al., 2000; Rigakis et al., 2001; Marnelis et al., 2007). These discoveries complement the well-known hydrocarbon fields of Albania, including the recent discovery of the Shpiragu prospect (Albania, Velaj, 2015). A key characteristic of both Western Greece and Albania is that evaporites have been drilled and outcrop in both countries, within the so-called Ionian Zone (Fig. 1). Regional seismic profiles have shown that diapiric movements in Triassic evaporites deformed pre-existing compressional and extensional structures, resulting in the formation of NNW-SSE trending diapiric walls (Karakitsios, 1992, 1995; Kamberis et al., 1996; Kokinou et al., 2005; Marnelis, 2007; Roure et al., 2004; Velaj, 2015; Karakitsios et al., 2017). Against this backdrop, geological, geophysical, stratigraphic and well data are combined with seismic information and regional structural transects in this work to:

a) Document the complex structural styles in Western Greece and Albania and understand its relationship with underlying evaporite sequences;

b) Identify main hydrocarbon migration pathways (tectonic or stratigraphic) in the areas analysed in this work;

c) Identify potential petroleum systems in Western Greece and Albania, focusing on the similarities and differences between the two areas in terms of lithology, porosity, permeability, source-rock extent and thickness.

d) Propose a model for the evolution of the External Hellenides – Southern Albanides thrust- and fold belt from Oligocene to Early Pliocene.

In summary, new models are proposed in this work to explain the structural styles and geometries of the fold-and- thrust nappes in Western Greece and Albania. The magnitude of crustal shortening based on published works, as well as the nature and depth of the detachments formed below these fold-and-thrust nappes, are compared and contrasted for Western Greece and Albania.

2. Geological setting

2.1. Meso-Cenozoic evolution of the Albanides and External Hellenides

The Albanides and Hellenides are part of the Alpine Orogenic Belt, itself comprising a broad region of Late Mesozoic-Cenozoic tectonic convergence with distinct branches in SE Europe: the Apennines, Albanides, Dinarides and Hellenides (Fig. 1). Within these branches, distinct tectonic zones with differing structural, depositional and metamorphic evolutions are recorded onshore and in offshore exploration data. In particular, the Meso-Cenozoic evolutions of the External Albanides (Kruja, Ionian and Sazani zones) and the most External Hellenides (Gavrovo or Gavrovo-Tripolitza, Ionian and Pre-Apulia or Paxos zones) were controlled by: a) the relative movement of the Adriatic-Apulia microplate within the Nubia (Africa)-Eurasia plate boundary zone (Nocquet and Calais, 2003), and b) the closure of the Mesozoic Tethyan Ocean. Prevailing tectonic structures in the Albanides and External Hellenides comprise west-verging thrust faults and folds denoting double-verging geometries (IGRS-IFP, 1966; Jacobshagen, 1986; Brooks et al., 1988; Underhill, 1989; Clews, 1989; Karakitsios, 1992, 1995). Main geodynamic events related to the evolution of the Albanides (Shallo, 1990, 1992; Melo et al., 1991a, b; Kodra and Bushati, 1991; Robertson and Shallo, 2000) and Hellenides (Dewey et al., 1973; Aubouin et al., 1976; Robertson et al., 1991) are summarised below and in Table 1. To simplify this work, we herein refer to the Albanides and Hellenides respectively by the abbreviations (A) and (H):

1. **Triassic**: Materialising a pre-rift stage, the Triassic period records the deposition of evaporites over basement units of unknown age and nature, likely comprising metamorphic or igneous rocks

in the Ionian zone (H/A). Above these evaporites, the Foustapidima limestone (H) and dolomites (A) dominated Upper Triassic deposition in the region. Sequences of breccias and evaporites were accumulated in the Pre-Apulia zone (H) during the Triassic, while dolomites are documented in Upper Triassic successions of the Sazani zone (A). Significantly a major structural element, the Vlora-Elbasan Transfer zone, or VET, limited the northwest extent of Triassic evaporites in Albania (Fig. 1). The VET was responsible for significant palaeogeographic changes in the Ionian basin (Roure et al., 2004), with the deposition of a large volume clastic deposits (4-8 km thick) occurring at this time within the Peri-Adriatic depression (Zappaterra, 1994, Albpetrol 1993; see Transect 2 in Figure 5).

2. **Early-Middle Jurassic**: Continental rifting during the Early-Middle Jurassic was responsible for the development of pronounced ridges (Gavrovo/Kruja and Pre-Apulia/Sazani zones) and basins (Ionian/H/A and Pindos/Krasta-Cukali zones), both in Western Greece and Albania. Shallow marine carbonates and pelagic carbonates/radiolarites (BP, 1971; Karakitsios, 1992, 1995) predominated at this time in the Ionian and Pre-Apulia zones (H), whereas dolomites are present in the Ionian and Sazani zones of Albania (A). Anhydrites were also drilled in the Pre-Apulia zone, e.g. well Gaios-1x in Paxos, starting from a sub-surface depth of 1805 m.

3. **Cretaceous**: Deep-water carbonates predominate in Lower to Uppermost Cretaceous post-rift strata of the Ionian (A) and Pre-Apulia/Sazani zones (H/A) (Swennen et al., 1998; Vilasi et al., 2006; Le Goff et al., 2015). Shallow-water carbonates were accumulated in the Gavrovo zone during, at least, the Upper Cretaceous (Senonian) to Eocene (A)/Lutetian (H) times. Plate collision between the Apulia microplate and Eurasia took place from Late Cretaceous to Early Eocene (Dewey et al. 1973; Jones and Robertson, 1991; Doutsos et al. 1993).

4. **Late Eocene**: Erosion of the Pindos Ranges supplied important volumes of sediment to foreland basins in the Gavrovo and Ionian (H) zones from the start of the Late Eocene (Faupl et al., 1998, Sotiropoulos et al., 2003; Dewever et al. 2007; Karakitsios and Rigakis, 2007). This resulted in the deposition of a turbidite sequence in Greece and Albania the so-called "Pindos flysch", recording a thickness between 2.5 km and 5 km (Jenkins, 1972; Sotiropoulos et al., 2003; Kamberis et al., 2005). The deposition of "flysch" strata in the Gavrovo zone has been dated as Late Eocene (Priabonian) (IGRS-IFP, 1966; Fleury, 1980; Sotiropoulos et al., 2003; Kamberis, et al., 2005; Sotiropoulos et al., 2008; Pavlopoulos et al., 2010). In addition, the deposition of transitional beds (3-10 m) separating older carbonate and pure flysch beds probably took part during the Eocene, as pointed out by Sotiropoulos et al. (2003) and Kamberis, et al. (2005).

The "Pindos flysch" of the Ionian zone of the External Hellenides (H) is considered to be Oligocene-Early Miocene (Bellas, 1997), whereas more recent studies reported Late Eocene-Late Oligocene (Kamberis et al., 2005) and Oligocene (Sotiropoulos et al., 2003) ages for this same sequence. In turn, Velaj (2015) documented that similar strata on the Ionian zone of the External Albanides is Oligocene-Aquitanian in age. In the Ionian (H) zone, the transition from carbonate to clastic sedimentation (flysch) is marked by the deposition of a 20-50 m thick marly interval (Sotiropoulos et al., 2003). The carbonate-flysch transition (Late Eocene in the Hellenides, Early Oligocene in the Albanides, according to Albpetrol, 1993) has also been documented at well Artemis-1 in the NW Peloponnese, where it comprises a 21 m interval of limestones, marly limestones, and subordinate sandstones (Kamberis et al., 2005).

5. **Neogene-Quaternary**: A syn-orogenic sequence (Molasse) dominates the Neogene geology of the Sazani zone and the Peri-Adriatic depression (A). The deposition of Middle Miocene to Pliocene molasses in the Peri-Adriatic depression (or Pre-Adriatic foredeep basin) started in the

Langhian (Gjika et al., 2001; Velaj, 2015). The formation of this foredeep basin is related to a compressional tectonic regime (Gjika et al., 2001). Tectonic uplift (Roure and Sassi, 1995; Roure et al., 1995; Roure et al., 2004) and tectonic instability (Karakitsios, 2013) dominated the Eocene-Langhian evolution of the Sazani (A), Pre-Apulia (H) and Ionian (H) zones. Hence, the Pre-Apulia zone is considered to form a transitional zone between the Apulia foreland and the Ionian Basin. At outcrop, proof of tectonic instability include: a) the presence of large-scale eastward-verging slumps and olistostromes in the Upper Eocene carbonate sequence (e.g. marble quarry of Araxos in Northwest Peloponnese), b) tectonic-driven deposits observed in the basal parts of the flysch sequence (e.g. Mavri Miti cape in the NW Peloponnese), and c) tectonic movements and associated slope instability recorded in the Ionian (A/H) zone (Kamberis et al., 2000). It is worth stressing that important Oligocene slumping is also observed in both the Antipaxos and Paxos Islands (Karakitsios, 2010).

2.2. Compressional and extensional deformation styles

An important aspect is that the pre-Mesozoic basement is probably involved in the compressional deformation of the SW Greece. Thrusted basement nappes, identified below Triassic evaporites of variable thickness, are able to affect (and propagate into) the post-salt successions to reveal a combination of thick- and thin-skinned deformation across the western part of the Ionian and Pre-Apulia zones, in the so-called External Hellenides imbricate fold-and-thrust belt (e.g., Underhill, 1989; Kamberis et al., 1996; Kokkalas et al., 2013). Such a deformation style has also been identified in the units related to the internal parts of the Tuscany-Umbria palaeogeographic domain of the Adriatic Sea (Italy), where a rigid metamorphic basement controls deformation in the shallower parts of the crust. However, units in the more external parts of the Tuscany-Umbria palaeogeographic domain are solely detached at the level of Permo-Triassic evaporites, suggesting a thin-skinned deformation style (Bally et al., 1986).

A similar structural style to Tuscany-Umbria has previously been suggested for the western part of the Ionian (H) zone by Kamberis et al. (1996) and Kokinou et al. (2005). In addition, thin-skinned and basement deformation has been proposed for the evolution of the Ionian zone in NW Greece by Doutsos et al. (20060, Marnelis et al. (2007) and Kokkalas et al. (2013). Finally, the pre-Mesozoic basement was identified as having a close control on shallow deformation when considering both alternative interpretations of Kamperis et al. (1996) for the Pre-Apulia zone. The concentration of recent seismic activity at a depth between 6 km and 16 km in the foreland domain of the External Hellenides, offshore Zakynthos Island (Kokkalas et al., 2013), also confirms a combined thin – and thick skinned style deformation of the External Hellenides, proving that structures in the pre-Mesozoic basement are active at present (see also Boyer and Elliott, 1982; Coward and Potts, 1983), including significant parts of the Gavrovo and Pindos zones (e.g. Jenkins, 1972; Skourlis and Doutsos, 2003; Sotiropoulos et al., 2003; Xypolias and Doutsos, 2000; Kokinou and Kamberis, 2009).

Direct evidence that the Ionian (H) zone is thursted over the Pre-Apulia zone was found in well Filiates-1 (IGRS-IFP, 1966; Karakitsios, 2013). In fact, shortening in the foreland domain of the Western Hellenides affects a ~6-7 km thick sedimentary succession of Mesozoic carbonate rocks and evaporites, as well as foredeep siliciclastics dated as Miocene to Pleistocene in age (Monopolis and Bruneton, 1992; Kamberis et al., 1996; Kokkalas et al., 2013).

2.3 Structural controls on potential hydrocarbon and geoenergy prospects (Ionian and Pre-Apulia Zones)

Fold-and-thrust belts in the most external Hellenides (Pre-Apulia or Paxos, Ionian and Gavrovo-Tripolitza zones) and Albanides (Sazani, Ionian, Kruja zones and the Peri-Adriatic depression) result from the collision between the Apulia plate and the Eurasian continent (Dewey et al., 1973). The Ionian zone, the tectonic unit with the greatest hydrocarbon and geoenergy potential, consists of Triassic evaporites and Ladinian-Rhaetian limestones overlain by lower Jurassic-Upper Eocene carbonates and Upper Eocene-Oligocene flysch (Karakitsios, 1992, 1995, Kamberis et al., 2000, 2005). The pre-evaporite basement, possibly of Permo-Triassic in age, does not outcrop in the Ionian zone. However, based on regional seismic sections, the pre-evaporite basement possibly underlies both the Ionian and Pre-Apulia zones in the southern part of the study area (Kamberis et al., 1996; Kokinou et al., 2005). Complex structures of the most external Hellenides and Albanides (mainly the Ionian and, to a lesser extent, the Pre-Apulia zone) are further affected by significant halokinesis and diapiric movements of Permo-Triassic evaporites (Monopolis and Bruneton, 1982; Kamberis et al., 1992; Kokinou et al., 2005; Karakitsios, 2013; Velaj, 2015).

The Pre-Apulia zone consists of Triassic to Langhian carbonates and is considered to be the “slope” of the Apulia Mesozoic carbonate platform, which belongs to the Adria microplate. Seismic data reveal that Apulia is also affected by compressional tectonics, whereas its eastern boundary is marked by the Ionian zone thrust detected to the west of Corfu Island (Flores et al., 1991, and this study).

The actual extent of the Ionian (H/A) and Pre-Apulia zones is shown in the geological map in Fig. 1. Main tectonic structures and strike-slip faults associated with the geological evolution of the study area are also shown. The tectonic boundary between the Ionian (H) and the Gavrovo zones in Western Greece coincides with the Makrynoros (Gavrovo), Varassova and the Skolis mountains in Etoloakarnania and NW Peloponnese (Sotiropoulos et al., 2003; Pavlopoulos, 1983; Kamberis et al., 2000, 2000a, and this study). This same boundary is detected west of Dumre in Albania, ending SE of Tirana (Fig. 1). In parallel, published seismic reflection studies have confirmed the boundaries of the Ionian (H)/Gavrovo zones and Ionian (H)/Pre-Apulia zones as occurring to the west of Corfu Island, in the South Ionian Sea (Monopolis and Bruneton, 1982; Kamberis et al., 1992; Kokinou et al 2005; Kokkalas et al., 2013) and extending northwest of Crete Island (Andronikidis et al., 2018, this study). These boundaries are of great significance because they limit, to the west, underexplored areas of the Ionian (H) and Pre-Apulia zones (H/A) with known petroleum potential.

Stratigraphic successions in the Ionian zone (H/A) consist of Triassic evaporites, Triassic to Eocene carbonates, Tertiary flysch and Neogene marine to continental clastics (Monopolis and Bruneton,1982; Kamberis et al., 2000a; Zelilidis et al., 2003; Karakitsios, 1995; Rigakis and Karakitsios, 1998; Karakitsios et al., 2017 and this study, Fig. 2). Sedimentary basins in the Pre-Apulia zone comprise Upper Triassic to Middle Jurassic anhydrites and carbonates (Table 1 and references therein). Evaporitic sedimentation ceased with the onset of Ionian rifting. Hence, limestones in the Pre-Apulia zone, often intercalated with cherts and marls, reflect pelagic environments. During the Late Cretaceous-Oligocene, sedimentation occurred in shallow-platform and slope environments; Miocene sediments consist of marls, sands and clays, while Pindos flysch deposits are not known in the Pre-Apulia zone.

Neogene stratigraphic sequences with known hydrocarbon shows and developed fields in Albania and Western Greece are shown in Fig. 3. Productive sandy intervals in both countries include the following intervals, starting from the oldest: a) Messinian, as documented by the Patos, Marinze and Kucove fields of Albania, b) lower Pliocene (Selenice bitumen field, Divjake, Balsh gas fields in Albania), as well as possible gas productive horizons in wells KAT-101, KAT-102 and Peristeri-1 in Greece, and c) Middle-Upper Pliocene, with solid bitumen occurring in the Selenice field of Albania. Gas sands, although marginal in terms of their economic value, have been drilled in the NW Peloponnese within Middle-Upper Pliocene strata (see wells KAT-101, KAT-102 and KAT-103, Fig. 3). Drilled sequences include concentrations of dry (biogenic) gas whose potential should be further explored. In contrast, wet gas is found in most surface seeps, inside Triassic evaporites in onshore wells, and in the West Katakolon field in association with oil and the catagenetic process. Wet gas shows have been also detected in clastic sediments (stratigraphic traps) drilled by well KA-105 (Fig. 3, Kamberis et al., 2000, well location in Kamberis 1987, Kamberis et al., 2000).

3. Data and methods

Six (6) regional transects, roughly oriented in an E-W direction perpendicular to the main regional structures, were completed in this work (Fig. 1). These transects are located in the region between South Albania and Southwest Greece (South Ionian Sea), and cross the External Albanides (Kruja, Ionian, Sazani and Peri-Adriatic depression) and the most External Hellenides (Gavrovo or Gavrovo-Tripolitza, Ionian and Pre-Apulia zones). The transects were compiled using new outcrop data, published geological data (maps and stratigraphic logs), borehole data, and re-interpreted seismic reflection profiles.

The geological map in Fig. 1 was compiled based on information from the geological and tectonic maps of Albania (IGRS-IFP, 1966; ISPGJ-IGJN, 1983, 1985; Robertson and Shallo, 2000; Velaj, 2001; Roure et al., 2004; Velaj, 2011, 2015), Greece (Bornovas and Rontogianni-Tsiabaou, 1983; Karakitsios and Rigakis, 2007; Zelilidis et al., 2003; Karakitsios, 2013; Kokkalas et al., 2013), published articles and industry reports (Godfriaux, 1968; Aubouin et al., 1970; Duerr et al., 1978; Burchfiel, 1980; Alther et al., 1982; Seidel et al., 1982; Kamberis 1987, 1992; Dinter and Royden, 1993; Kilias et al., 2001). In detail, well data and stratigraphic information concerning the Upper Triassic-Eocene passive-margin sequences, the synorogenic flysch, and the synorogenic/synkinematic Neogene Molasse filling the Peri-Adriatic depression were collected from various sources (Geological Institute of Albania; Diamanti et al., 1995; Roure et al., 2004, Karakitsios and Rigakis, 2007; Karakitsios, 2013; Velaj, 2015). In addition, we present the distribution of the main source rocks (Fig. 11) outcropping in the Ionian Zone in Western Greece and Southwestern Albania, based on previous information (IGRS-IFP, 1966; 1:500.000, IGME, 1983, Geological map of Hellas after Bornovas and Rondogianni-Tsiambaou) and field work implemented in the context of the present study. Information concerning a) the interpretation of seismic facies, b) structural models for the External Albanides, c) the magnitude of crustal shortening experienced by the Gavrovo/Kruja, Ionian (H/A) and Pre-Apulia/Sazani zones in the External Hellenides and Albanides (Woodward et al., 1989; Sylvastrava and Mitra, 1995; DeCelles et al., 2002; Teixell et al., 2003; Babault et al., 2013), d) oil and gas data for Albania over a time-period of 30 years (1965-1995), e) stratigraphic position of source rocks, f) reservoir lithologies and other related parameters from the oil fields and outcrops in Albania, were gathered from sources such as Diamanti et al. (1995), Gjika et al. (2001), Guri and Guri (1996), Dhima et al. (1996) and Velaj (2015). All these data are sumamrised in Tables 1 to 4.

Hydrocarbon exploration projects in Albania and Greece, and accompanying deep crustal studies, have acquired seismic reflection data, gravity and magnetic maps, and limited vertical electrical soundings. Seismic reflection data interpreted in both the External Albanides (Papa and Kondo, 1968; Finetti and Morelli, 1972; Paulucci et al., 1988; Guri and Guri, 1996; Dhima et al., 1996; Seitaj et al., 1996; Velaj et al., 1998; Xhufi and Canaj, 1999; Gjika et al., 2001; Frasheri et al., 2009; Jardin et al., 2011; Velaj, 2015 and references therein) and the External Hellenides (Monopolis and Bruneton, 1982; de Voogd et al., 1992; Truffert et al., 1993; Lallemant et al., 1994; Camerlenghi et al., 1995; Kamberis et al., 1996; Chaumillon and Mascle, 1997; Kamberis et al., 1998; Kamberis et al., 2000a, b; Fruehn et al., 2002; Le Pichon et al., 2002; Tay et al., 2002; Reston et al., 2002; Jones et al., 2002; Kokinou et al., 2005, 2006; Kamberis et al., 2005; Huguen et al., 2006; Marnelis, 2007; Kokinou and Kamberis, 2009; Makris and Papoulia, 2014; Andronikidis et al., 2018) provided important constraints to the regional transects in this work.

4. Interpretation of regional structural transects

4.1 Transect1

Transect 1 crosses the External Albanides from the Adriatic Sea towards the Ballaj-Divjaka gas field, which is located ~2 km to the NNW of the central part of the transect (Fig. 4). The Dumre oil field ends to the east near the boundary of between the Kruja and the Krasta zones (see Fig. 4 and the relative location of the Dumre oil field in Fig.1).

The most significant compressional structures in Transect 1 include: a) the boundaries between the Ionian-Kruja and Kruja-Krasta zones, b) the boundaries between tectonic nappes in the Ionian (A) zone (Kurveleshi anticline, Memaliaj syncline, Berati anticline), and c) small-scale internal thrusts in the latter tectonic nappes. Large reverse displacements of 11-13 km are documented in the Kruja thrust (KRU). In fact, thrust displacement in this structure may exceed 18 km near the eastern boundary of Transect 1 where the Kruja thrust joins the Berati thrust (BER) (Fig. 4).

Compression tectonics seems to affect a sedimentary sequence of approximately 7.5 km in which are included Mesozoic (Neocomian-Eocene) carbonate rocks and Oligocene flysch deposits (see Table 2). Nappe geometry is similar to that of the NW Peloponnese (Kamberis et al., 2000a) and Etoloakarnania (Sotiropoulos et al., 2003), where thrust displacement is at least 20 km and 10 km, respectively. Here, structural models consider an array of eastwards dipping thrusts (Gavrovo zone) showing an imbricate geometry.

Triassic evaporites in the Ionian zone (A) form a basal detachment zone for the overlying thrust nappes (Monopolis and Bruneton, 1982; Kamberis et al., 1996; Velaj et al., 1998; Marnelis et al., 2007; Kokinou et al., 2005; Velaj, 2011; Kokkalas et al., 2013). In Transect 1, evaporites crop out in the Memaliaj syncline belt near the Dumrea diapir, and are interpreted to extend to the east into the deeper parts of the transect (Fig. 4). This indicates that the Triassic evaporites exerted a significant control on the evolution of the fold-and-thrust belt of the External Albanides. Significantly, well Dumre-7 in the Memaliaj syncline resulted in a significant oil discovery in Oligocene flysch deposits .

West of the Kruja thrust fault (KRU), the Ionian zone (A) likely comprises an imbricate fold-and-thrust belt (the Berati, Memaliaj and Kurveleshi antiforms) with a basal detachment at a depth varying from 10 km to 24 km (Fig. 4). This fold-and-thrust belt comprises westward-verging antiforms bounded by east-dipping thrusts that sole out in an eastward-dipping detachment (Fig. 4). This same detachment separates folded Triassic-Eocene sequences from 'sub-detachment' basement units. The imbricate fold-and-thrust system ends offshore near the middle of the Peri-Adriatic depression, where a blind thrust-related anticline (PAA) is observed (Fig. 4). This structure forms a potential hydrocarbon trap.

It is worth noting that, in Transect 1, the Ionian zone (A) presents a complex set of stacked nappes in the central and internal parts of its supra-salt units (Velaj, 2015). A significant horizontal shortening is estimated for this latter region (see Table 2) at times approaching 60% (Bare et al., 2000). Back-thrusts showing moderate displacements (about 3 km) are rare in Albania, the exception being the eastern Kurveleshi anticlinal belt (Fig. 4). Nevertheless, the Lushnja field, located 4.5 km NW of Transect 1 (Fig. 4), may be associated with a back-thrust trap.

Based on our interpretations, we propose a few wildcat wells for future exploration, as indicated by the vertical dashed lines in Transect 1 (e.g. Lushnja, Fig. 4). The proposed well locations aim at drilling the Triassic-Eocene carbonate sequence, the Oligocene flysch of the Ionian zone (A), and foredeep clastic deposits of Upper Cenozoic age. However, integrated studies of trap integrity and local trap geometries should be completed before any well location is confirmed. In parts of Transect 1, Miocene-Pleistocene strata reach a thickness of 5 km to 8 km (Zappaterra, 1994; Velaj, 2011), and comprise potential source rock levels (lignite and coal) and reservoirs in Tortonian, Messinian and Pliocene deposits. In the region crossed by Transect 1, the main depocenter shifted eastwards during the Middle Miocene-Pleistocene, resulting in the formation of a hinterland-dipping monocline with strata growing towards the thrust front of the Orogen, where strata reach 11 km in thickness (Fig. 4). A similar structural style is depicted to the south of Transect 1, in western Greece, where a hinterland-dipping monocline composed of Lower Miocene to Pleistocene strata is 5-6 km thick (see Transect 5 in Fig. 8). These strata also extent to the southern Ionian Sea, west of the Kythira and Crete Islands (Kokinou E., Kamberis E., 2009), where Messinian evaporites and clays may also form a good quality caprock.

Normal faults are rare in Transect 1 and, when identified, show relatively small throws, a character proving that the region is dominated by compression. East-dipping thrusts, and especially the larger ones, are associated with local halokinesis and diapiric structures, which potentially act as principal hydrocarbon and heat/fluid migration paths. Sub-salt anticlines, as well as imbricated nappes in supra-salt flysch and carbonate units may form local traps. Hydrocarbon discoveries in Albania such as the Dumrea oil field, the Divjaka gas field (Velaj, 2015) and many other prospects associated with large, regional, thrusts (i.e. Visoka, Ammonica, Ballshi prospects) and sub-detachment structures (Shpiragu, Delvina prospects), support the interpretation shown in Transect 1 (Fig. 4). In addition, the Lushnja wildcat well in Albania has crossed shallow and deep oil shows in stacked, imbricated Triassic-Paleogene carbonates (Table 4).

4.2 Transect 2

Transect 2 spans the Ardenica-Vllamas-Kucove regions and is partly modified from Velaj (2015) to show the regional structure up to a depth of 6 km (Fig. 5, see location of Transect 2 in Fig. 1). The interpretation of this transect is based on well data (hydrocarbon-productive wells) combined with regional seismic information.

Cretaceous-Eocene carbonates predominate in Transect 2, where they are 1.2 km to 1.5 km thick (Fig. 5). These carbonates are overlain by Oligocene flysch and Neogene (Early Miocene to Late Pliocene) strata (Fig. 5). Key tectonic structures n Transect 2 include, from East to West: a) the Kucove anticline, b) the Vllamas anticline, c) the Patos-Marinez-Kolonje monocline, d) the Patos-Marinez anticline that overlies the Vllamas anticline at a depth of ~ 3 km, and e) the Ardenica flower structure, itself associated with thrusting and post-Early Pliocene ("Helmsi") back-thrust faulting. This back-thrust movement affected Tortonian-Upper Miocene and Pliocene strata (Fig. 5). Additionally, strata west of the Vllamas anticline appear to be partly inverted and folded (Fig. 5).

Tortonian-Upper Pliocene strata generally dip westwards (e.g. monocline Patos-Marinez-Kolonje in Fig. 5), a direction opposite from that of pre-Tortonian strata, a character resulting in the formation of onlap geometries at depth. These onlapping geometries indicate a phase of tectonic uplift, followed by erosion, during the Latest Serravallian-Early Tortonian, a structural configuration likely associated with halokinesis, not imaged in Transect 2, but likely related to the southern extent of the Dumrea diapir. The Dumrea diapir deformed both Pre-Neogene and Neogene units from the Late Tortonian to the present day. As a result, the Tortonian sedimentary pile thins to the east in Transect 2, while to the west its thickness reaches ~1.7 km (Fig. 5). Overlying Pliocene deposits also show a westward increase in their thickness (Fig. 5).

Productive oil fields occur in Oligocene flysch deposits (e.g. Kucove oil field), and are often sealed by a thick cap rock. This cap rock is composed of Triassic evaporites (Dumrea diapir, Fig. 4), Paleocene carbonates, flysch and Neogene deposits (the Patos-Marinez / Marinze, Kucove anticlines, Fig. 5), Middle Miocene and Pliocene strata (Patos Marinez monocline; Marinez, Kolonje, Vllamas anticline; Fig. 5) and Tortonian sediments (west Kucove syncline, Fig. 5). Pliocene sediments are also productive east of the Vllamas syncline. In addition, many of the productive hydrocarbon fields previously mentioned are related to the thrusting/reactivation of evaporites (Dumrea diapir) and reveal occasional oil shows at the surface (Memaliaj syncline). Migration paths of hydrocarbon traps are thus linked to: a) compressional structures (Patos-Marinez, Kucove anticlines, Ardenica flower structure), b) combined tectonic-stratigraphic structures (east Kucove, Vllamas oil fields) and c) stratigraphic traps in Middle-Upper Miocene/Tortonian deposits (Kucove syncline, Vllamas anticline and Patos-Kolonje syncline).

4.3 Transect 3

Transect 3 spans the Apulia platform (External Albanides) from the Ionian Sea and Karabruni (Sazani zone), through the Cika anticlinal belt (Tragiasi and Dhermi), ending close to the Shushika synclinal belt to the east (Fig. 6, see location of Transect 3 in Fig. 1). We developed this transect to better show the deformation styles of the outer Ionian (A) and the Sazani zones (A), focusing on the local back-thrusts and associated structures that occur in the latter zones (Fig. 6).

Transect 3 is dominated by imbricated nappes and possible out-of-sequence thrusts generated after the Middle Miocene-Upper Miocene boundary, likely after the Tortonian (Velaj, 2015). In particular, out-of-sequence thrusts associated with the Shushika syncline of the Ionian (A) zone deformed back-thrust faults and Lower Miocene deposits, and thus post-date their activity (Fig. 6). In Transect 3, the Cika anticline is the dominant structure and is associated with a main thrust (Tragiasi Fault) and a diapir (Dhermi salt structure). The basal detachment of the imbricated nappes was formed at the base of the Triassic evaporites and developed to a maximum sub-surface depth of 10 km. It is underlain by flysch deposits of Paleogene age. As a comparison, Transect 4 (Fig. 7) shows a basal detachment between 0 km and 12 km, while in Transect 1 (Fig. 4) its depth varies between 8 and 24 km.

Close to the A/H limit, the Cika anticline was thrusted westwards in order of 90 km (A) and 38 km (up to a maximum of 47 km) over a stacked sequence of Triassic-Serravallian strata (Transect 3, Fig. 6, Table 2). Evaporites extend up the Apulia platform, beneath the Karabruni peninsula, where a large scale (>14 km) back-thrust displacement is interpreted (Tragiasi area/A). This latter structure deformed an older (and structurally lower) thrust fault associated to the Ionian thrust (Fig. 6), as well as Mesozoic strata and Miocene-Pliocene deposits. The main thrust (Ionian/A zone), itself linked to salt diapirs, is possibly the principal hydrocarbon migration path in the region.

Based on the data above, a wildcat (well Tragiasi) with oil shows at 4-4.5 km in Lower Miocene and possibly Oligocene flysch deposits may be equated for the region. The seal units, in this area, are likely to comprise clayey intervals in Upper Miocene and Pliocene units. However, competent 3D closures and traps should be confirmed before drilling the putative location of well Tragiasi.

4.4 Transect 4

Transect 4 crosses the region between Corfu Island and North Ioannina and was partly modified from Velaj (2015). The modifications mainly concern the thrust faulting in the Shushica and Permeti synclinal belts and the Kurveleshi anticlinal belt. Transect 4 depicts the regional structure up to a depth of ~ 10 km (Fig. 7, see location of Transect 4 in Fig. 1). Main compressional structures, from east to west, occur: a) in the tectonic nappe of the Krasta/Pindos zone, and b) the Ionian zone of Albania (Berati, Kurveleshi and Cika anticlines). The nappe of the Krasta/Pindos zone is located to the east of the Permeti syncline and lies above a carbonate unit Triassic to Eocene in age (Ionian/A zone). This carbonate unit is thrusted over the top of the Oligocene flysch sequence. In this area, the pop-up structure of Permeti is formed at the base of the flysch. Providing that a competent 4-way closure is confirmed, this structure corresponds to a potential target in the Permeti synclinal belt.

The Zavrohon and the Kurveleshi salt structures, located west of the Permeti syncline, are associated with thrust faults that record significant displacements. Fault displacements in this part of Transect 4 (Fig. 7) are 16.5 km and 8.5 km, respectively, whereas they approach 10 km east of the Permeti syncline (Table 2). Total shortening has been estimated to be ~40% for the Ionian/A zone (see Roure et al., 2004).

West of Kurveleshi, thrust faulting resulted in the generation of a developed stack of thrust anticlines, i.e. a fold-and-thrust belt. Thrust faults sole out eastwards towards an eastward-dipping detachment in the Triassic evaporites. The depth of these evaporites can reach 12 km, and they reveal a significant role in the evolution of Kurveleshi fold-and-thrust system. Furthermore, multiple salt structures (e.g. the Kurveleshi and Berati anticlines) associated with the fold-and-thrust systems above generated important thickness variations in the Triassic evaporites. A ramp-thrust geometry is also identified at depth around the Shushika syncline-Cika anticlinal belt.

Transect 4 (Corfu-North Ioannina) shows evidence for Triassic evaporite diapirism around the Corfu Island, in association with a large scale thrust fault (Table 2), which records a relatively large thrust displacement (~35 km). Here, the Apulia zone occurs below the imbricate thrusts of the Ionian (A) zone.

The southern extension of the Berati belt towards Greece has been drilled by well Demetra-1, which reached a total depth of 3966 m. Drilling eventually resulted in the discovery of significant gas shows in Permo-Triassic evaporites, at a depth of 1900-3900 m, and underlying limestone/anhydrite units, at a depth of 3900-3966 m. Water and gas trapped in limestone/anhydrite were likely responsible for the high pressures encountered between 3900 m and 3966 m in this well, below which the drilling could not continue to reach the main reservoir targets (Mavromatidis and Kelessidis, 2009). Gas was detected but borehole tests were not completed. It is, nevertheless, useful to note that gas was detected at depths of around 2000 m and between 2700-2800 m. Oil shows were found at about 2200 m depth, at the location of a thrust fault. These data lead us to suggest a wildcat well at the location of the Permeti pop-up structure (see dashed line in Fig. 7). Clayey intervals in the flysch unit may comprise the caprock in this location. Eventually, another wildcat well is also proposed at the location of the Zavrohon salt structure (Permeti pop-up structure) with possible prospects occurring close to the top of Triassic evaporites.

Pliocene strata act as the detachment layer for some of the large thrusts at the westernmost part of Transect 4 (Fig. 7a). This configuration is similar to that encountered at well Filiates-1 in Epirus, where Tortonian deposits, about 48 m thick, occur below Upper Cretaceous/Eocene carbonates

(1192-1710 m deep, and 518 m thick) of the Ionian (H) zone (Fig. 1). At the location of well Filiates-1, the carbonate series of the Pre-Apulia zone (Triassic-Eocene) is 6.0 km thick, dipping to the east, and affected by thrust faults showing small displacements. A fault displacement of ~5.5 km is comparable to structures mapped around the Zakynthos Island (see Transect 5 in Fig. 8). These data support the drilling of new prospects in Eocene strata of the Pre-Apulia zone, particularly around Corfu East and Xara, providing that future 2D or 3D seismic data are able to confirm trap integrity in thrusted sequences of Upper Triassic-Eocene age (Fig. 7a).

In the internal and central Ionian (A) zones, hydrocarbons shows are also related to thrust faults and salt structures (e.g. Berati and Kurveleshi systems, and Kyllini system, respectively), which likely favour hydrocarbon migration in Cretaceous-Eocene carbonates and flysch deposits. Oil shows are also documented in Epirus along thrust faults, at the marginal areas of thrust-related anticlines (Thesprotikon, Kassidiaris) and synclines (i.e Botsara syncline considered as the south extent of Memaliaj syncline in Greece). In the Botsara area, oil shows are located at the thrust fault tectonic contact between Mesozoic-Eocene carbonates and younger rock units (flysch, Neogene deposits). Economic prospects may be present below the Triassic evaporites, in Triassic to Eocene carbonate units of the internal and central Ionian/A zones, as well as in the sub-thrust platform area of the Apulia zone, consisting of Triassic to Miocene carbonates. In the Apulia zone, Triassic economic prospects may be present in the Triassic and upper Jurassic-Lower Cretaceous carbonates (Flores et al., 1991). In this latter zone, economic prospects may be present at depths between 3.0 km and 4.5 km.

4.5. Transect 5

Transect 5 spans the region between Zakynthos Island and the Skolis Mountain in NW Peloponnese (see Fig. 8 and corresponding location in Fig. 1). The deformed units in the southern part of Western Greece, across Transect 5, belong to the Gavrovo, the Ionian (H) and the Pre-

Apulia zones, the latter also documented in the islands of the Ionian Sea and in neighbouring offshore areas (Fig. 8). The Gavrovo zone is observed in the easternmost part of Transect 5, where it is structurally placed on top of the Upper Eocene-Oligocene flysch of the Ionian (H) zone (Fig. 8). This same flysch sequence (Ionian/H zone) comprises low-angle, eastward-dipping detachment horizons (Ds) that reach depths of 8 km (Table 2) in the easternmost part of Transect 5 (Fig. 8). Furthermore, a sequence of thrust faults converges on this eastward-dipping detachment, forming an imbricate fold-and-thrust belt deforming both the flysch and Cretaceous-Eocene limestones in the Gavrovo zone (Fig. 8).

The boundary between the Gavrovo and Ionian (H) zones is expressed by the Gavrovo thrust fault (GTF), the westernmost boundary of the previously mentioned thrust-fault sequence (Kamberis et al., 2013). The GTF presents a listric geometry with a high angle (about 70^0) frontal segment (effectively, the Skolis Mountain) and a low-angle geometry in its deeper portion (Fig. 8). This structural style is probably related to thin-skinned tectonics, an interpretation supported by both surface and well data (see well Apollon-1, reaching a total depth of 1710 m, in Fig. 8). In well Apollon-1, located in NW Peloponnese, no significant gas seeps or oil shows have been detected in both Upper Cretaceous-Eocene carbonates (1192-1710 m deep, and 518 m thick) and the overlying flysch sequence of the Gavrovo zone, showing a minimum thickness of 892 m. In contrast, the Upper Cretaceous/Paleocene carbonate of the Kruja zone (A) in Albania comprises important source rocks (black shales and dolomite) that are oil prone (Diamanti et al., 1995; Gjika et al., 2001; Roure et al., 2004). The Upper Jurassic-Eocene carbonate sequence (H) in well Filiatra-1 (3756 m), SW Peloponnese, returned asphalt shows at a depth between 705 m and 3756 m (Kamberis, 1987).

The Ionian zone (H) in Transect 5 reveals an Upper Cretaceous/Paleocene carbonate sequence with a minimum thickness of 389 m, sealed by a thick (1986 m) flysch succession with no significant oil shows in well Artemis-1. In Albania and offshore the Adriatic coast, this same interval comprises reservoir rocks in the Visoke, Gorishti-Koculi, Delvine, Cakran-Mollaj and Ballsh-Hekali oil fields. It is worth mentioning that only minor hydrocarbons shows have been found in evaporite units in Greece, the only exception being well Demetra-1 in Epirus (NW Greece), although with no definite confirmation due to the lack of production tests because due to technical reasons. The low porosity and permeability of Cretaceous-Eocene reservoirs (<0.5 %) at well Artemis-1 (Karakitsios and Rigakis, 2007; Mavromatidis et al., 2004; Kamberis et al., 2005; Marnelis et al., 2007; Mavromatidis and Kelessidis, 2009) suggests that hydrocarbons have already experienced Tertiary migration from most Epirus' prospects.

The basal detachment of the Kruja zone in Albania presents a similar geometry to Greece's, but its depth exceeds 12 km at the eastern portion of Transect 1 (Fig. 4). In NW Peloponnese, the total thrust displacement recorded by hanging-wall strata in the Gavrovo zone (Table 2) is of the order of 20 km, corresponding to a shortening rate of 1.76 mm/year (Kamberis et al., 2000). It is at least 10 km and 1 mm/year, respectively in Etoloakarnania (Western Greece), suggesting important nappe tectonics as well (Sotiropoulos et al., 2003). The thrust-and-fold belt affecting the Gavrovo zone has been inactive since the Late Oligocene, but still records important contribution of the Triassic evaporites to its overall geometry. The emplacement of the Gavrovo imbricate thrusts on top of the Ionian (H) zone was responsible for widespread halokinesis from east to west, and diapiric movements within the Triassic evaporites promoted the folding of the Mesozoic-Tertiary carbonate and flysch series of the Ionian (H, A) zone (Kamberis et al., 2000). In the Miocene, tectonic shortening and inversion progressively affected the Ionian (H) zone, Triassic evaporites, and probably the Paleozoic basement in the eastern portion of Transect 5 (Fig. 8). This same Paleozoic basement was identified in seismic profiles from onshore NW Peloponnese (Kamberis et al., 1996; Kokkalas et al., 2013) and in offshore basins around the West Patraikos Gulf, Cephalonia and Zakynthos (Kokinou et al., 2005, Fig. 9).

Main thrusts of the Ionian (H) zone possibly acted as the principal hydrocarbon migration paths in Transect 5. This interpretation is supported by the multiple oil seeps mapped across this transect, occurring in wells Sosti-1 and Artemis-1 and at the surface (Kyllini) (Fig. 8). Other oil shows detected in the southeastern part of the Zakynthos Island (wells Keri and Agios Kyrikos) and the oil seeps in the Laganas area (Zakynthos Island) are associated with a Miocene to Pliocene-Quaternary sequence of clastic deposits accumulated around the this same Island (Zakynthos channel; Nikolaou, 1986), and also under the Kyllini salt structure (Fig. 8). Finally, the base of the Mesozoic sequence in the Ionian/H and Pre-Apulia zones correlate with poorly defined seismic reflector (Kamberis et al., 1996; Kokinou et al., 2005). This reflector coincides with the top of pre-evaporite strata (Paleozoic sequence), and it is detected at a depth of 5 km to 8 km in the Pre-Apulia zone, in the western part of Transect 5 (Fig. 8). In Transect 5, the Pre-Apulia zone occurs below the Ionian (A) zone, reflecting a thrust displacement at regional (nappe) scale probably exceeding 21 km in length (Table 2). Finally, it is worth noting that the normal faults depicted to the west of the Ionian thrust front may correspond to extensional structures formed in the foreland domain since, at least, the uppermost Miocene.

4.6. Transect 6

Transect 6 crosses the offshore region to the south of Zakynthos Island-Katakolo peninsula, towards the Alfeios River in NW Peloponnese. It depicts the regional structure to a depth of about 8 km (see Fig. 10 and corresponding location in Figs. 1 and 10). Transect 6 is based on seismic information, geological and well data (wells WKA-1 and Alfeios-1) and the work of Kamberis et al. (2000a).

Main compressional structures in this transect are three imbricated tectonic units (wedges) of Mesozoic carbonates and Triassic evaporites (Ionian/H zone), detached from the Paleozoic basement by Triassic units (Fig. 10). Thrust faults are generally low-angle structures, except for their shallower frontal parts, and accommodated significant horizontal displacement (Fig. 10). The structural style of Transect 6 is similar to Transects 1 and 4; they all show imbricated units whose geometries were controlled by thin-skinned tectonics above Triassic evaporites. Their basal detachment is not recognised in Transect 6, but is likely to occur within Triassic evaporites at a depth of about 8 to 10 km (Table 2). The total shortening of the Ionian (H) zone ranges between 20% and 30% as proposed by Karakitsios (1995) for the Ionian zone in Greece (Table 2). It is worth stressing that the West Katakolon field offshore was discovered in one of those imbricate thrusts, within a Lower?-Middle Jurassic to Eocene carbonate sequence (Fig. 10).

A large salt structure occurs in the westernmost part of Transect 6, and is associated with a thrust fault of regional scale (Fig. 10). This thrust fault bounds a potential fault-related trap to the east and offsets thick (>4.5 km) Pliocene and Pleistocene deposits, predominantly clays and silts (Fig. 10). Located southeast of Zakynthos Island, the thrust is in the continuation of the West Katakolon field, despite occurring a water depth of >1000 m. Diapiric movements are active at present and deform Holocene deposits, and the sea floor, in Transect 6 (Fig. 10). Halokinesis, together with thrusting, formed large diapiric structures in the neighbouring area of south Zakynthos, which may enhance the migration of hydrocarbons to potential traps. These either comprise stratigraphic traps (pinch-outs) in the Mesozoic carbonate series and overlying Neogene strata, or footwall highs in the Mesozoic carbonates. Finally, a large normal fault with a significant throw (>2.2 km) and heave, is present west of the previously mentioned salt structure.

5. Petroleum systems sampled in exploration wells

Data concerning all recognised petroleum systems in the Albanides and External Hellenides are summarised in Table 3. In detail, we focus on the nature of the main source rocks (Fig. 11), the oil/gas reservoir-rocks, caprocks, the types of structural traps observed, as well as the estimated or proven depth of hydrocarbon shows in Albania and Western Greece. Key information from Table 3 includes:

- Messinian strata, together with Tortonian and Pliocene clastics (sandstones), record a significant reservoir potential. In the Patos, Marinze, Divjake, Panaja and Kucove oil fields, Middle Jurassic (Toarcian) source rocks mainly charge these reservoirs. More sparingly, Upper Triassic, Lower and Upper Jurassic source intervals (Kucove oil field) may also charge them.
- Cretaceous/Eocene carbonates are the main reservoir intervals in Albania (e.g. Gorishti-Koculi, Cakrran-Mollaj, Delvine, Finiq-Krane, Visoke and Ballsh-Hekali oil fields). In Greece (W. Katakolon oil/gas field) they are charged by Lower-Middle Jurassic source rocks present in the Ionian zone.
- Oligocene flysch intervals have been drilled in the Drashovice oil field (A). They are charged by Upper Triassic source rocks (shales).
- Messinian reservoirs contain heavy to light oil with densities between 12^{o} and 35^{o} API.
- Cretaceous/Eocene carbonates contain oil with 16^{o} and 37^{o} API (oil) and rarely 52^{o} API condensate.
- Finally, flysch sediments contain heavy oil with 10^{o} API (e.g. Drashovice oil field).

The matrix porosity of Upper Cretaceous-Eocene limestone in some oil fields (i.e. Cakran/A) ranges from 2.5 to 3.0%, with a maximum value reaching 6% when including fracture-related porosity in such estimates. In addition, the matrix porosity of fractured limestone varies between 2.4% and 2.5% with a maximum value of 8% (Prifti and Muska, 2010). In contrast, sub-thrust intervals in Albania (i.e. sub-thrust intervals beneath the Tragjasi anticline in the Cika belt) comprise fractured Upper Cretaceous-Eocene carbonate, possibly of the Ionian zone, where the reservoir succession presents a very low porosity around 0.019% (well Kanina-1 /5362 m t.d.). Oil with an API density of 16^o-20^o has been detected in well Kanina-1 (Kurveleshi belt), to the east of Transect 3 (Fig. 6). In this well, no flows were recorded during the tests.

Well Shpiragu-1 drilled sub-thrust Upper Cretaceous-Eocene carbonates beneath the Berati belt to reveal light oil (37^oAPI) in reservoirs with good reservoir porosity. Reservoir porosity in well Kanina-1 is close to that estimated (<0.5%) in some of the boreholes drilled in NW Peloponnese (well Artemis-1) and in Etoloakarnania. In contrast, the Lower to Middle Jurassic-Eocene fractured carbonates of the West Katakolon field (NW Peloponnese), show comparable reservoir porosity values (1.5-3.8%) to those reported in the Cakran field (A) by Prifti and Muska (2010). This characteristic is partly due to the sub-aerial exposure, karstification and erosion these fractured carbonates experienced from the Early Miocene to Late Pliocene. In addition, the porosity in the Pre-Apulia carbonate series (neritic-mixed facies) ranges between 4 and 13% (Karakitsios and Rigakis, 2007).

In what source-rock potential is concerned, the Pre-Apulia zone contains multiple neritic-pelagic carbonate intervals in Upper Triassic, Lower and Middle Jurassic strata (Karakitsios and Rigakis, 2007), as well as in Pliocene and Miocene successions - the latter with no significant hydrocarbon potential in Greece. Upper Triassic, Lower and Middle Jurassic source rocks are also present in Albania. Conversely, Neogene successions in the Peri-Adriatic depression - and especially sandstone layers within the Neogene strata - showed significant reservoir potential in the Ballaj and Divjaca gas fields.

The carbonate series of the Gavrovo zone contains organic-rich intervals in well Filiatra-1(H). Paleocene/Eocene limestones present good matrix and vuggy porosities (5.0-8.0%) that are enhanced by a fair fractured porosity of 1.0-3.0% (A) (Diamanti et al., 1995; Prifti and Muska, 2010). In the Upper Cretaceous-Eocene platform carbonates (Kruja zone) are recognised source intervals with significant TOC values of 3.95% (Prifti and Muska, 2010).

Hydrocarbons are abundant in the Peri-Adriatic depression, where the thickness of the Neogene clastic deposits ranges between 5 km and 7 km. Source rocks and reservoirs are present in the Neogene succession of Albania (Fig. 3). Proven source rocks in Greece are the Toarcian series (Fig. 11), which can locally exceed 340 m in thickness, whereas locally they may either present very small thickness, may be totally absent (Sosti-1), or even not yet been drilled in some wells (e.g. West Katakolon-1). In Albania, the same series exceed 450 m, whereas locally may reach a much greater thickness of ~ 600 m. However, the Toarcian series generally constitutes the most prolific source-rock interval of the Ionian Basin (Palacas et al., 1986; Karakitsios et al., 1988). Other potential source rocks are recognised within the Middle-Upper Jurassic (Vigla shales) and in organic-rich shale intervals in Triassic strata (Karakitsios and Rigakis, 2007, Fig. 11).

Figure 11 has been prepared based on field data and presents the extent of oil seeps in Albania and Western Greece. It shows that seeps are less frequent to the south of Epirus and almost absent to the south of Aetoloakarnania and in Peloponnese. Unique exception may be the Sosti-1 well (NW Peloponnese), where a lower Cretaceous source level, showing a thickness a few tens of meters, may be present.

It is important to stress that oil and gas shows offshore Italy, where Triassic evaporites contain source intervals consisting of bituminous dolomites with intercalations of gypsum and clays (Burano Formation), extend eastwards into Albania and Greece (Paulucci et al., 1988). In addition, Upper Triassic source rocks charged the Oligocene flysch sediments drilled in the Drashovice oil field of Albania. The shale intercalated with evaporites at the Kastro Kyllini outcrop (NW Peloponnese) may also include potential source rocks (Fig. 11). This should be the subject of future research and more geochemical analyses. It is also interesting to note that surface oil shows have been detected at the Loutra Kyllinis compressional structure, at the contact between carbonates and Triassic evaporites (see transect 5).

Carbonate reservoirs (Cretaceous/Eocene) contain productive levels in many an oil field in Albania, comprising fractured, karstified and eroded units in Greece and in West Katakolon marginal oil/gas field offshore the Peloponnese. In the Katakolon field, effective fracture porosity is significant, whereas primary porosity is less significant. In fact, porosity and permeability generally record greater values in Albanian wells when compared to Greece (Diamanti et al., 1995; Guri and Guri, 1996; Dhima et al., 1996; Gjika et al., 2001; Prifti and Muska, 2010, this study) (Table 3).

Messinian clastic reservoirs have values of O/C gravity, measured in API units, that range between 12^{o} and 35^{o} (oil/gas). The value of O/C gravity in Cretaceous/Eocene carbonates mainly ranges between 16^{o} and 37^{o} API (oil) and rarely exceeds 52^{o} API (condensate). Flysch sediments show lower O/C values, generally less than 10^{o} API (Drashovice oil field). Finally, O/C values for the Cretaceous/Eocene carbonate series in Western Greece is 28^{o} API (West Katakolon oil field).

Primary hydrocarbon reservoirs in the Albanides and External Hellenides are the Cretaceous/Eocene carbonate series, while the Oligocene flysch (sandstones) contains secondary reservoirs (Table 3). This has been confirmed by geological data from oil fields in Albania, both in sub-and supra-thrust structural positions, and by the West Katakolon field in Greece (Ionian zone/H). Neogene sedimentary sequences in Albania record a significant hydrocarbon potential and contain proven oil/gas reservoirs (mainly sand beds) in the Peri-Adriatic depression (Table 3). Cretaceous (dolomite/limestone) and Eocene organogenic platform carbonates in the Gavrovo/Kruja zones may include both source (gas prone) and reservoir intervals (Roure et al., 2004; Prifti and Muska, 2010; Velaj, 2015). This has been documented at outcrop in Albania, by oil shows in wells (i.e. Filiatra-1/H) and by gas shows in well Apollon-1, in West Peloponnese. However, there has been limited exploration of hydrocarbon plays in both in sub- and supra-thrust positions, particularly when considering sub-thrust anticlines.

In the Pre-Apulia zone, potential oil/gas reservoir rocks are recognised in the Jurassic and the Cretaceous carbonate series, as well as in the Triassic argillaceous dolomite (well Sazani-1, Roure et al., 2004). Exploration of these plays in Western Greece, where just a small number of wells crossed this succession around the Paxos Island and onshore Albania (Sazani peninsula), has been thus far limited. In the Pre-Apulia zone, structural traps comprise large-scale, broad, anticlines such as the Vrachionas anticline in Zakynthos and the Paxoi-Gaios-1x anticlines, which do not present any significant hydrocarbon accumulations, e.g. wells Zakynthos-1 and Paxos-1 in Greece. In contrast, thrust-related anticlines in the Ionian H/A zone that were sub-aerially exposed, karstified, eroded, and intensely fractured (West Katakolon/H; Shpiragu/A fields), comprise the traps with the greatest hydrocarbon potential.

Finally, potential source rocks and reservoirs may also occur in Neogene clastic deposits, i.e. in shaley beds of deep-water Miocene successions around the Zakynthos channel and Kyparissiakos Gulf (Karakitsios and Rigakis, 2007, Karakitsios, 2013).

6. Discussion

6.1 Structural styles in Western Greece and Albania and their relationship with underlying evaporite sequences

The External Hellenides/Albanides fold-and-thrust system is characterised by the successive thrusting of tectonic nappes with imbricate and duplex structural styles, the latter of which are more frequent in the internal Ionian zone (Transects 1, 4 Figs. 4, 7). Compressional tectonics progressively affected the Gavrovo and the Ionian zones (A) since the Late Bourdigalian-Langhian (Transect 2, Fig. 5), ending at the Miocene-Pliocene boundary (Transect 1, Fig. 4). This resulted in uplift and erosion of large parts (or even the entire) Lower Miocene sediments in the Peri-Adriatic depression (i.e. West of Lushnja; Fig. 4). Langhian-Serravallian strata in this region were deposited on top of the Oligocene flysch, whereas Lower Miocene sediments are observed beneath

Mesozoic-Tertiary units east of the Peri-Adriatic depression. The contact between Langhian-Serravallian sediments and the Mesozoic-Tertiary units corresponds to a low-angle eastward-dipping unconformity in the generally monoclinal successions filling the Peri-Adriatic depression. Stacked thrust nappes are recognised in Lushnja (A), dramatically increasing the total thickness (>20 km) of the stacked Mesozoic-Tertiary units to the East.

An important detail in this work is that out-of-sequence thrusts may occur in the central and eastern parts of Transect 1 (Fig. 4, Memaliaj synclinal belt) and Transect 2 (Fig. 5, Kucove basin and Vlammas anticline). This indicates a pre-Tortonian, or Latest Serravallian, episode of tectonic uplift and erosion of the Lower Miocene sequence. Such uplift and erosion probably affected large parts of the Middle Miocene sequences (Transect 2, Fig. 5, Vlammas anticline). Diapiric movements at Dumrea should be related to the out-of-sequence thrust faulting recorded at this location, which occurred together with back-thrusting at Pliocene level. This resulted in the formation of pop-up structures with significant hydrocarbon potential in the Lushnja (Fig. 4) and Ardenica fields (Fig. 5). Back-thrusts complete the structural style of this part of the Ionian (A) zone. Compressional tectonics was also associated with two main episodes of uplift and erosion that took place in: a) Pre-Tortonian times (likely in the latest Bourdigalian), and b) before the Upper Pliocene (West Katakolon field in Greece), probably with a more localised character in the Kucove field (Fig. 5). Finally, crustal loading by the orogen and overlying sediments resulted in regional subsidence towards the east, forming the Peri-Adriatic depression in Fig. 5. A similar subsiding structure has been observed offshore Zakynthos and in NW Peloponnese (Kamberis et al., 1996, 2000b).

Tectonic deformation in the Pre-Apulia zone took place since the Early Pliocene. Compressional tectonics and strike-slip movements occurred in this part of the Western Hellenic Margin from Pleistocene to recent times, and are associated with the Hellenic subduction zone (Underhill, 1989; Kamberis et al., 1996; Kokinou et al., 2005, 2006; Kokkalas et al., 2013; Karakitsios, 2013;

Karakitsios et al., 2017). The structural evolution of the External Hellenides is also influenced by normal faults progressively formed in the Gavrovo, Ionian (H) and Pre-Apulia foreland basins. These normal faults present significant throws between 300-400 ms (TWT) in seismic sections from central to southwest Greece (Kamberis et al., 2005) and they offset the Gavrovo, Ionian (H) and Pre-Apulia foreland basins close to the westward propagating thrust front. Normal faults form over sub-thrust faulted blocks in these foreland basins. They were active since the Latest Eocene (?)-Earliest Oligocene, probably until the displacement of the Gavrovo unit onto the Ionian (H) zone (Miocene), and the Ionian (H) zone onto the Pre-Apulia zone in the Early Pliocene.
Strike-slip and normal faults intersect compressional structures at high angles, resulting in significant displacement (~ 2 km in some places). In the External Hellenides, offshore strike-slip zones are located east of Lefkas/Kefallonia (KEF), southeast of Kefallonia/SEK (Kamberis et al., 1996; Kokinou et al., 2005, 2006), west of Lapithas Mountain (LAP) and in North Kyparissia (KYP) (Fig. 1). In addition, strike-slip zones are mapped onshore in the NW Peloponnese (Moni Maritsas, Kalfas-Kaletzi, Eleochori, Prodromos, for location see in Kamperis et. al. 1987, 2000) and Epirus, where the Petoussi E-W trending sinistral fault zone (PEP) presents a lateral displacement of about 1.5 km. They are considered to be tectonic features formed during the westward propagation of thrusts in the Miocene times. Most of these faults correspond to ENE-WSW trending dextral and ESE-WNW trending sinistral strike-slip faults. Finally, extensional structures (normal and strike-slip faults revealing local transtension), active since the Early Pliocene times, superimposed the pre-existing compressional structures and further deform the fold-and-thrust systems documented in this work (Kamberis et al., 2000).

The thrusting of the Ionian (H) zone over the Pre-Apulia zone (along the Ionian thrust) likely occurred after the Messinian (Kokkalas et al., 2013; Karakitsios et al., 2017), as documented by the Mesozoic limestone of the Ionian (H) zone, which overlies the Messinian and Miocene sequences deposited in the Pre-Apulia platform domain. Thus, the compressional structures formed in the Pre-Neogene-Mesozoic sequence of the Ionian (H/A) zone have been sub-aerially exposed, karstified, and fractured for a long time due to extensional tectonics. This process produced significant secondary porosity in the Mesozoic sequence of the Ionian (H/A) zone until the deposition of Pliocene and Pleistocene sediments above, as documented in the West Katakolon field in Greece and by the Amonica, Ballshi, Finiq-Krane and many other hydrocarbon fields in Albania. Structural traps corresponding to folds and monoclines in the hanging-wall blocks of thrusts, later truncated and fractured the productive sub-thrust plays (Albania) formed in Mesozoic/Early Tertiary strata (Table 3), forming the main prospects in both the Albanides and External Hellenides.

Regarding the Gavrovo and the Ionian foreland basins of the Hellenides, thrusting and shortening (convergence) rates are low, approaching 1 mm/year (Table 2). In Albania, shortening rates reach 2 mm/year if one considers the Oligocene flysch as the main detachment (Roure et al., 2004). Assuming that deformation was continuous in the External Albanides in the Middle Oligocene, shortening values are related to the average convergence rate, wihc is calculated up to 25 Ma before the present-day. In Albania, the average convergence rate and shortening values are 2 mm/yr and 35-56% respectively, whereas in Greece are 1 mm/yr and 30-40% (Table 2).

Structures that accommodate tectonic shortening in the Pre-Apulia/Sazani and the Ionian (H/A) zones consist of imbricate thrust systems and associated (regional-scale) folds. These structures were formed over a Triassic detachment that is located at a depth ranging from 8 km to 12 km in Greece, reaching more than 13 km near the Greece-Albania border, probably exceeding 22 km into Albania (Diamanti et al., 1995; Kamberis et al., 1996, 2000; Kokinou, et al., 2005; Kokkalas et al., 2013; Karakitsios, 2013; Velaj, 2015). The Triassic evaporites acted as the main detachment level, comprising one of the main parameters controlling the regional petroleum systems that can be correlated from Albania to Western Greece. Flysch deposits of the Ionian (H/A) and Gavrovo/Kruja zones, acted also as main detachment horizon for the Gavrovo and the Pindos nappes, respectively. Furthermore, Posidonian shales and schists of Lower-Mid Jurassic ages, clayey limestone and shaley intervals (Lower Cretaceous) in the Ionian zone (Table 3), as well as shale intervals in the clastic deposits forming the younger Molasses, acted as detachment levels in both countries but at a minor, local scale. Halokinesis that followed the compressional tectonics are responsible for the significant variations in the thickness in Triassic evaporites. Narrow salt structures are evident at the locations of the pre-existing NNW-SEE trending tectonic axes (i.e. thrust related anticlines, synclines) as confirmed by already referred published geological and seismic sections from Western Greece and South Albania (Kamberis et al., 2000, 2005, Kokinou, et al., 2005; Kokkalas et al., 2013, Velaj, 2015).

In summary, the more important parameters controlling the petroleum system of the Albanides and External Hellenides include: a) overthrusting at the scale of the tectonic nappe, or geotectonic zone, b) internal deformation (horizontal shortening) expressed in percentage values, and c) the shortening rates experienced at local and regional (nappe) scales (Table 2). In Table 2 are shown geological and seismic information concerning the nature and the depth of detachment horizons, structural styles and deformation styles recognised in each geotectonic zone, aiming to provide an integrated view of the parameters controlling the petroleum systems of Albania and Western Greece.

6.2 Similarities and differences among hydrocarbon prospects in Albania and Western Greece

According to Velaj (2015), the Upper Triassic evaporites in Albania consist of gypsum, anhydrites, salts, multicoloured clays and breccias with interbedded dolomite and thin organic-rich shales. Evaporites are widespread in the Kurvelshi anticlinal belt, whereas gypsum and anhydrite predominate in the Berati and Cika belts (Velaj, 2001). In Greece, Triassic evaporites comprise halite and anhydrite with intercalations of limestone and dolomite, as well as gypsum and anhydrite at the base of the evaporitic series (Fig. 8, Kamberis et al., 2000; Rigakis et al., 2001; Pomoni-Papaioannou et al., 2004). These evaporites present remarkable seal competence and ductility (Fig. 11). Triassic evaporites, and also a great part of Upper Cenozoic deposits (shales and silty shales), are relative ductile showing laterally continuous lithology (Kamberis, 1987); therefore, they can form potential caprocks (Table 4) in canopies and structural 'overhangs' in combination with thick accumulations (>2.5 km) of Upper Pliocene-Pleistocene clastic deposits. As examples of this setting we report the West Katakolon field and other potential hydrocarbon structures mapped offshore in the Kyparissiakos Gulf (NW Peloponnese). These capping deposits reach a maximum thickness of 3 to 4 km when considering Miocene sediments as seals. It is worth noting that the oil shows in the southeast area of Zakynthos occur in Miocene sediments. These sediments form the lower sedimentary succession in the Zakynthos Channel (Transect 5, Fig. 8) and in the deeper areas of Kyparissiakos Gulf (Transect 6, Fig. 10). It is also important to stress that oil shows in the Eocene carbonates outcropping (Kamberis, 1987) in the Filiatra area (NW Peloponnese) come from Miocene source rocks (clay series), which have been deposited in evaporite basins (Rigakis, 1999).

Triassic evaporites reveal p-wave velocities on seismic data ranging between 5800 m/s and 6300 m/s (Kokinou et al., 2005) and acted as the detachment horizon for the Mesozoic-Tertiary thrust units of the Ionian (H) and the Pre-Apulia zones (Kamberis et al., 1996; Kokinou et al., 2005; Kokkalas et al., 2010; Kokinou et al., 2017). Comprising mainly anhydrites in Greece, the interface between the Triassic evaporites and the Mesozoic sequence of Pre-Apulia zone may be a simple stratigraphic boundary (Fig. 9 and Kokinou et al., 2005). Diapiric movements are strongly related to the surface oil seeps (Dumre diapir, Botzara syncline, Kyllini diapiric structure), as well as with some ill-defined amplitude anomalies observed in the seismic profiles, at the contact of the evaporite with the overlying carbonate series of the Ionian zone in both the External Albanides (Kurveleshi anticlinal belt, western part of the Berati anticlinal belt) and Hellenides (i.e close to Kyllini diapiric structure, SE Zakynthos Island diapir). Halokinesis took place in pre-existing, compressional structures, i.e. in the tectonic axes of NNW-trending thrust faults (Kamberis et al., 1996), thrust-related fractured anticlines, synclines and folds, and occasionally at the older or younger extensional structures (Kokinou et al., 2005, Figs. 4-10). Salt structures resulted in the generation of buried highs (Kurveleshi anticlinal belt) and outcropping salt (Dumrea, Delvina, Corfu, Zavrohon, Xara, Filiates, offshore Kefallinia Island and Kyllini), and cross the Mesozoic-Tertiary carbonate series. They also deformed the overlying Mesozoic-Tertiary units (Velaj et al., 1998), generating the complex structural style documented in the most external parts of the Ionian (H/A) and Pre-Apulia/Sazani (H/A) zones. Well data from Greece and Albania confirmed the broad sub-surface extension of the Triassic evaporites in both countries. They also occur in the Pre-Apulia zone (Underhill et al., 1988; Kokinou et al., 2005) whereas they are almost absent in the Kruja/Gavrovo zones. The thickness of the Triassic evaporites ranges between 1.7 km (well Demetra-1 in Epirus) to 3.5 km in the Ionian (H) zone (Kokinou, et al., 2005). This thickness may locally exceed 3 km - and 6 km in some location (Memaliaj syncline) - when associated to large scale structures such as the Kurveleshi anticline, the Permeti syncline, the Cika (A) and Zavrohon (H) belts. The thickness of these evaporites generally decreases westwards in the outer Ionian zone (Transect 1/Fig. 4) and below the Pre-Apulia platform margin (H), where it reaches approximately 1.7-1.8 km (Fig. 8).

Triassic evaporites may also be organic-rich, comprising oil-prone source rocks with significant potential (Table 3). These source rocks alternate with carbonates and dolomitic carbonates deposited at the margins of the salt basins (reservoirs), as well as caprock of distinct lithologies (e.g. wells Dumre-7 and West Katakolon-1). Furthermore, salt structures are often accompanied by bitumen shows at the surface (e.g. Zakynthos Island, Trifos/Etoloakarnania, Botsara basin/ Epirus, Dumrea /Albania). Bitumen shows are usually detected at the unconformable contact with carbonates (Loutra Kyllinis in NW Peloponnese, Tryphos) or filling thrust faults crossing Mesozoic-Tertiary units such as carbonates and flysch (e.g. Delvinaki area in Epirus; Karakitsios and Rigakis, 2007). Oil shows also occur at the contact between flysch and Bourdigalian clastic deposits in wells Lavdani-1 and Lavdani-2 (Karakitsios and Rigakis, 2007). Unconformable and tectonic contacts are leading paths for the migration of hydrocarbons to the surface. In addition, diapiric movements also resulted in folding and deformation of Late Cenozoic sequences and the consequent formation of hydrocarbon traps in porous strata (conglomerates, sands) interbedded and sealed by clayey intervals (e.g. well Peristeri-1 in NW Peloponnese).

In the Ionian zone, active kitchens are currently located in the under thrusted rock units. Because of increasing burial, hydrocarbons generated during the Pliocene-Quaternary (see lithological columns in Figs. 2, 3) are likely to be more mature and lighter than hydrocarbons generated earlier in the Late Oligocene-Early Miocene time (see Transects 5, 6, Fig. 11 in Roure et al., 2004). Although many carbonate anticlines have lost the hydrocarbons that were trapped early in Late Oligocene-Early Miocene due to Miocene (Pre-Tortonian) erosion, distinct hydrocarbon phases are likely to have been mixed in most of the productive carbonate fields. An alternative hypothesis is to consider vertical migration from the footwall or active thrusts, mainly across or along the intervening thrust faults, and possibly tectonic features related to latter extension. Other authors also corroborate this hypothesis (Karakitsios, 2001; Rigakis, 2007; Karakitsios, 2013). In such a case, future exploration should consider not only the shallower Cretaceous-Eocene carbonate reservoirs, but also the deeper Triassic-Liassic dolomite, providing that good seals can be documented in the intervening Posidonia schist and other Jurassic and Cretaceous shaly intervals (i.e. Kourenta anticline, Karakitsios, 2013). The main source rocks at this level are: 1) organic-rich shales in the Triassic evaporite series of the Ionian (H/A), Pre-Apulia, and Apulia zones, 2) organic-rich shales in the Jurassic formations of both the Ionian (H/A) and Pre-Apulia zones and 3) organic-rich shales in the Cretaceous formations of the Ionian (H/A) zone (Fig. 11). Less significant source rocks are a) the flysch of Oligocene-Aquitanian age, b) the Bourdigalian Pre-Molasse sequence (Ionian zone/A) which generates gaseous hydrocarbons (Velaj, 2001, 2015) and c) the Tortonian, Pliocene clastic formations of dry/biogenic gas (Peri-Adriatic depression, NW Peloponnese) in many Neogene basins (Ionian zone, Pre-Apulia, Sazani, and Apulia zones).

6.3 An updated structural evolutionary model for the External Albanides and Hellenides

Based on the analysis performed here, we propose a structural evolutionary model of the External Hellenides/Albanides foreland during Oligocene - Early Pliocene via schematic cross sections (Fig. 12). It is worth pointing out that the geometry of the compressional pattern of the Albanides is mainly related to two types of compressional structures: a) imbricate, b) duplex type, mostly depicted in the internal and the central Ionian zone, and to a much lesser extent to complex imbricated nappes in the internal domain of the Ionian zone (A). Imbricate, and lesser duplex type compressional structures, related to the structural repetition (stacking) of Cretaceous/Eocene carbonate reservoir rocks and flysch (cap-rock), are also present in the northernmost part of the External Hellenides (Transect 4, Fig. 7). In addition, if the pre-evaporitic Permian basement in the Western Greece is part of the thin-skinned orogenic wedge (east of Pindos thrust), the Phyllite-Quartzite unit should be the subducted pre-evaporitic continental basement of the Pre-Apulia and Ionian (H) zones (Karakitsios and Rigakis, 2007). Such structures are present in the offshore area of Katakolon peninsula (Transect 6, Fig. 10). Thin-skinned geometry better expresses the tectonic pattern across the Albanides and NW Greece (Transects 1, 3, 4 in Figs. 4, 6, 7). Furthermore, thin-skinned (Table 2) and eventually mixed thin and thick-skinned tectonics better express the structural style of the Zakynthos Island and the neighboring offshore area of the Pre-Apulia domain (Kokinou et al., 2005; Kokkalas et al., 2010, this study) as well as the eastern part of the Ionian (H) zone (Transects 5, 6, Figs. 8, 10) and possibly in the NW Peloponnese area.

The thrusting of the Gavrovo zone on the Ionian (H) zone (>10 km in Etoloakarnania, >20 km in Peloponnese) is approximately of the same order of that measured in Albania (11-18 km) (see Table 2). Shortening average rate and internal (intrazone) deformation of the flysch reference horizon (Middle Oligocene) are greater in Albania (2 mm/yr and 40%, respectively, Roure, 2004) compared to Western Greece (1 mm/yr, Etoloakarnania) and NW Peloponnese (23%, Table 2 according to Robertson group plc, Internal report of DEP EKY, 1990). Based on seismics and well data, the thrusting-displacement of the Ionian (H) zone on the Pre-Apulia zone ranges from 15 km to 21 km (South Ionian Sea), whereas it probably exceeds 50 km (Roure, 2004) at the Albania/Greece border (Table 2). Internal deformation also indicates greater thrust displacements in Albania (20 to 30 km in Berati belt, Velaj, 2015). However, these values fit well to imbricate and duplex compressional patterns, mainly in Albania and NW Greece. In the Pre-Apulia zone, internal deformation possibly varies between 15% and 25% (Karakitsios, 1995). The imbricate compressional pattern may be more suitable for this external zone. In the Apulia zone, internal deformation seems to be small, mainly expressed by thrust faults with small thrust displacements (Transect 4, Fig. 7a).

The flysch of Ionian (H/A) zone and the Triassic evaporites of the Ionian (H/A) and Pre-Apulia/Sazani zones are the main detachment horizons for the thrusts of the Gavrovo/Kruja and Ionian (H/A) zones, respectively (Table 2). These detachment horizons have been assigned with respect to the sea level using both seismic information and well data at a depth greater than 10-24 km (Transect 1, Fig. 4), 12-13 km in the Greek-Albanian borders and 3.5-12 km in Greece, respectively. The evaporites and the flysch also acted as detachment horizon for the internal deformation of the Ionian (A) zone (Kurveleshi anticlinal belt, Transects 1, 4, Figs. 4, 7).

In both Greece and Albania, evaporites are relatively thick (1.3-3.5 km) and can be as thick as 6.0 km. Occasionally, the evaporites are associated to significant diapirisms and diapiric movements (i.e. Memaliaj Botzara syncline/Dumrea diapir, Berati anticlinal belt/Zavrohon diapir), but they constitute a thick cover that does not allow the seismic signal to penetrate and image the pre-salt structure in detail. Thus, the real extent of the underlying basement (Paleozoic) and its structural style is difficult to reveal using seismic data alone (Kokinou et al., 2005). Nevertheless, the nature of the basement is possibly metamorphic, showing seismic velocities ranging from 5.4/5.8 to 6.1/6.3 m/sec. Furthermore, the evaporites and the flysch present good cap-rock characteristics (Transects 1, 4, Table 4) for the underlying repetitions of carbonate and flysch sequences (duplex) or imbricates in overthrust deformation patterns (i.e Kurveleshi anticline belt, Memaliaj/Botzara synclinal belt), both associated to the evaporite detachment (Ionian zone). Imbricates and broad anticlines, formed in the subthrust autochthonous units (Apulia, Sazani, Paxos/Pre-Apulia zones), may offer deeper perspective leads.

The most External Hellenides were affected by three phases of compression. These phases took place during the Early-Middle Miocene, the Intra-Pliocene and the Intra-Pleistocene, respectively (Sorel et al., 1992), while three unconformities (Pre-Neogene, Early Pliocene and Late Pliocene) corresponding to well-distinguished seismic reflectors, are recognised in Western Greece (Kamberis et al., 1996, 2000). The Pre-Neogene reflector may correlate to the Pre-Tortonian-Upper Miocene and Pre-Pliocene erosion-surfaces, respectively, which are observed at Ardenica-Vllamas area in Albania (Transect 2, Fig. 5). In this area, compressional tectonics combined with the erosional and karst surfaces resulted in the formation of stratigraphic traps (Patos-Marinez syncline) in the Peri-Adriatic depression (Patos-Marinez oil fields) and the Kucova area (Kucova oil fields), and mixed stratigraphic-structural traps at the location of thrust-related anticlines (Patos-Marinez, Kucova anticlines) when these structures are covered by Pliocene and Tortonian deposits (Transect 2, Fig. 5).

7. Conclusions

In the context of the present work, a multidisciplinary approach that took into account previous geological studies, drilling and seismic data, main tectonic events, thrust displacements, shortening rates and the type and depth of the main detachment horizons, was used to a) update the models related to the structural architecture of the External Hellenides and Albanides forelands and the associated oil systems, b) indicate the hydrocarbon migration pathways, c) highlight the similarities and differences of the petroleum systems in Western Greece and Albania and, d) provide a combined model for the evolution of the External Hellenide-Southern Albanides thrust- and fold belt from Oligocene to Early Pliocene.

The structure and evolution of the Hellenic and Albanian fold-and-thrust belt system is of great significance for the exploration and exploitation of hydrocarbons in the study area. The zones of the External Hellenides and Albanides thrusted each other westwards, during Eocene-Pliocene/Pleistocene times. This orogenic process resulted in the formation of a pile of Mesozoic-Tertiary thrust units, showing a thickness from 12 km to more than 24 km. During this orogenic process each of the thrust units (Gavrovo, Ionian, Pre-Apulia/Sazani zones, Peri-Adriatic depression) successively suffered an internal compressional deformation resulted in the formation of imbricates (Pre-Apulia, Ionian zone, Gavrovo zones) or imbricates and duplex structural styles (central, internal Ionian zone) above main basal detachments. These detachments are the Triassic evaporites for the Ionian and the Pre-Apulia and the Ionian flysch for the Gavrovo zone. The detachment faults associated with the Triassic evaporites gently dips eastward reaching a depth of at least 12-13 km to the south and exceed 22 km to the north of the study area. The significant increase of the depth of the Triassic detachment to the north is related to the duplex or rarely triplex styles (Ionian, Gavrovo zones) formed above the sub-thrust units, which comrpise the autochthonous foreland units (Apulia, Pre-Apulia/ Paxos, Sazani zones). The late alpine compression mechanism (Early Burdigalian-Early Pleistocene), offered good prospects for exploration (folds, thrust fault related fractured anticlines, synclines) in different structural styles (imbricate, duplex and eventually more complicate ones), in the overthrust units (Ionian, Gavrovo) and eventually in the subthrust. In the above-mentioned structural styles, the Triassic evaporites acted as an effective seal, occasionally associated with flysch (Shpiragu-1 well). Flysch, or flysch combined with Pre-Molasse and Neogene sediments also offer effective seals (E. Lushnja proposed well location at the boundaries of Ionian zone and Peri-Adriatic depression (Transect 1). The folded subthrust units (Pre-Apulia/Paxos, Sazani zones) seem to contain perspective leads (Mesozoic-Tertiary carbonates) and potential traps, if their 3D closure is certain. However, in the study area the depth of these traps leads may vary from 2.5 km (proposed well location Corfu East in Transect 4) to more than 4.5 km (proposed well location West Xara -1 in Transect 4) or even more than 6.0 km (Transect 5). The complex structural architecture of the External Hellenides and Albanides foreland is controlled by thin and - probably - mixed thin- and thick-skinned deformation (SW Greece) of the Meso-Cenozoic succession with reference to the detachment levels of the Triassic evaporites and the Paleozoic basement (Transect 5). The Paleozoic basement has been partly detected by seismic researches (Transect 5). However, we suggest that the contact of the basement (Paleozoic series) with the Triassic evaporite layer (basal detachment), in general corresponds to a slightly wavy-shaped litho-seismic horizon, which locally is folded and eventually comprises imbricate structures. These structures may contain analogous to those in Italy deep perspective plays. The depth of these plays, vary from 6.5-7 km to 10 km (western and central part of Transect 5). However, more systematic, seismic exploration with modern technology is necessary to image in detail the Paleozoic basement and the potential structural traps formed in the Paleozoic, if porosity is enhanced at depth.

Regarding the petroleum systems (hydrocarbon genesis, migration and trapping) in the External Albanides and the Hellenic forelands, the main conclusions are as follows:

- The main source rock levels are common in both systems corresponding to Lower Cretaceous shale/carbonate levels and Middle-Upper Jurassic shales (Ionian zone). Source rocks are also detected in the Upper Triassic-Lower Jurassic (outcrops) and Upper Triassic fragmented black shale levels/ in Albania and W. Greece (Ionian zone), comparable to those in Italy (Lower Triassic of Burano formation). In SW Greece the latter could correspond to a potential, but not proven, source rock outcrop in Kyllini Peninsula (NW Peloponnese). However, more detailed investigation is suggested for the potential Triassic source rocks especially regarding the W. Greece. The thickness of the source rocks significantly varies from the north (Albania) to the south (W. Greece). Specifically, the thickness of the Toarcian Posidonia shales varies from (0?) m (W. Katakolon - 1 well), or eventually from a few meters (Sosti - 1 well), to 340 m (outcrops/wells Epirus, W. Greece), to more than 450 in Albania.
- The TOC (%) content of the outcrops also decreases from north to south, especially regarding the Upper Triassic and the Lower Jurassic-Lower Toarcian outcrops, with TOC content to be up to 38.5 (%) and 52 % in Albania and up to 16% and 19 % in Greece. The effective porosity values concerning the Upper Triassic - Lower Jurassic and the Lower Cretaceous carbonate reservoirs are up to 7.0 % in Albania.
- Reservoir intervals are expected to be present in the Jurassic and the Cretaceous carbonate series regarding the Pre-Apulia zone (Paxos-1 well) and the Paleogene/Eocene carbonates in the Gavrovo zone (5-8% matrix and vuggy porosity in

Albania), whereas not organic reach intervals are referred in the Gavrovo zone (Filiatra-1 well, Greece). To the contrary the Pre-Apulia zone contains Upper Triassic, Lias and Malm source rock levels (Paxos/Gaios-1 well).

- Concerning the hydrocarbon traps, broad anticlines are present in Pre-Apulia zone, thrust fault-related hanging anticlines, synclines in Gavrovo/Kruja and Ionian zones of Greece and Albania. The broad anticlines are expected to contain more perspective plays (Kucove, Dumre, Zavrohon, W. Katakolon anticlines/Ionian zone).
- Many hydrocarbon discoveries have occurred in the Peri-Adriatic depression in Albania where productive plays occur in Tortonian, Messinian and Pliocene sand reservoirs charged from Mesozoic rocks (e.g. the Patos-Marinza and Kucova oil fields). In the Peri-Adriatic depression, there also are plays comprising sandy Messinian-Tortonian (e.g. Panaja gas field) and Pliocene units (e.g. Divjaka gas field) charged by clastic rocks (Molasse).
- Upper Miocene and Pliocene deposits (sands) record good cap rock characteristics in the Peri-Adriatic depression in Albania. Messinian evaporites and clays may document seal potential for the Upper Miocene (Tortonian) sands of Albania and the southern areas of the Ionian Sea (Kyparissiakos Gulf, SW Kythira). In addition, the Lower Miocene deposits are accounting as potential source rocks in southern areas of the Ionian Sea (Kyparissiakos Gulf, SW Kythira).
- Significant accumulations of biogenic gas in sand levels are recorded in the Neogene - Pleistocene successions in offshore Katakolon wells (NW Peloponnese). However, the latter needs more accurate seismic information and probably shallow drillings (> 600-1700 m) in a future biogenic (dry) gas exploitation in the Katakolon Peninsula and the neighbouring Pyrgos basin (NW Peloponnese).

Finally, it is emphasized that most oil and gas fields, in Albania and W. Greece are present in the central Ionian zone. Oil and gas fields are less in the internal Ionian zone (Berati anticlinal belt) and the Peri-Adriatic depression. Furthermore, oil and gas seeps are observed in the Hellenic foreland (central Ionian zone) and occasionally in the internal and the external Ionian zone. This is likely related to the overthrust structure, which includes imbricates or repetition of the Mesozoic-Tertiary carbonate sequences (central and internal Ionian zone), as well as subthrust duplex structures on the overthrust sheets (Shpiragu field).

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Table and Figure captions

Table 1: Chronostratigraphy and tectonic events of the Gavrovo/Kruja, Ionian, Pre-Apulia zones and the Peri-Adriatic depression.

Time/Tectonic events	**Gavrovo-Tripolitza(H)/ Kruja(A)**	**Ionian (H)/Ionian(A)**	**Peri-Adriatic Depression(A)**	**Sazani (A)**	**Pre-Apulia (H)**
Pliocene-Quaternary Mud diapirisms, late shortening	Erosion (A) lacustrine and beach sediments (H)	Post Alpine sediments (H)-erosion (A)	Molasse (synkinematic series/A)	Erosion (A)	Marine marls, sands (H)
Messinian Messinian evaporitic seal Tortonian Langhian-Serravallian shortening Bourdigalian ……………………. Aquitanian-growth anticlines	Molasse (A) Emersion (A)	Molasse (A) Post Alpine sediments (H) Local emersion (A) Molasse (A) Pre-Molasse Flysch (A)	Turbidites (A) Molasse(A) Deep water (A)	Turbidites (A) Calcareous sandstones (A)	Marls, marly, turbiditic limestones (H)
Oligocene-Lower Miocene (H) to Pleistocene (A) onset foreland flexure	Lower Oligocene/synflexural Flysch A/H Upper Eocene-Oligocene boundary transitional beds (Sotiropoulos et al., 2003; Kamberis et al., 2005)	Lower Oligocene A/H–Aquitanian A/H Flysch Upper Eocene (NW Peloponnese /Etoloakarnania) transitional beds A/ Albetrol, 1993;Velaj, 2015; Artemis-1 well/H (Kamberis et al., 2005)	SynflexuralMolasse (A) /Langhian-Pleistocene (Roure et al., 2004; Velaj, 2015)	Emersion (A) Carbonates, Shallow marine facies (Flores et al., 1991). It probably represents an isolated carbonate-bank of the Apulia platform margin	Pelagic limestone (H)
Eocene-Paleocene passive margin Upper Eocene-Tectonic instability Gavrovo-Tripolitza (H)/sea bottom instability during Upper Eocene (Ionian zone) /slumps	Emersion/Bauxite A/H- some internal areas (?) Limestone H/A +Priabonian flysch (H) (Fleury, 1980; Kamberis et al., 2005)	Paleocene-Eocene Pelagic (to slope? towards Sazani platform/A) limestone H/A Slumps/olistostromes within the Upper Eocene carbonates/Lower members of the flysch sequence (Kamberis et al., 2005). Upper Eocene flysch (H)	No data (it has not been reached by drillings up to the present day). It is expected to be of basin type (Ionian zone ?)	Emersion (A) Bauxite (A) Platform, Carbonates (Flores et al., 1991)	Pelagic (H) and breccias limestone (Karakitsios and Rigakis, 2007), locally hiatuses (H), Bauxite

Cretaceous, passive margin (A)	Limestone (H) Platform (A)	Senonian limestone (H) Vigla limestone (H)- carbonate turbidite(A)		Barremian, mainly Platform, Carbonates (A)	Limestone with chert nodules (H), similar to Ionian zone (Triassic-Eocene) / Wells Gargano Est, Aquila-1(Flores et al., 1991)
Upper Jurassic-Eocene (Filiatra-1well-3754m, Kamberis, 1987) with asphalt shows (from 705 m to the 3756 m, depth/H Jurassic-synrift extension	Limestone Platform (H)	Posidonia beds H/A Siniais limestone (H) and Pantokrator limestone (H)			Dolomitic limestone, limestone, anhydrite-intercalations/H (Paxi-Gaios-1x well, from 1805 m in depth, Lower Jurassic) / (Karakitsios and Rigakis, 2007)
Triassic Breccias		Foustapidima limestone (H) Dolomite (A) Shale/clay Evaporites H/A, (shale fragments within breccias)			Evaporites, black shale intercal/H

Table 2: Shortening (published works) and thrusting calculations for both the External Albanides (A) and Hellenides (H). Symbol explanations: 1*/Sotiropoulos et al. (2003), 2*/Robertson group plc, Internal report/ DEP EKY (1990) see also references at the end of this text, 3*/Roure et al. (2004), 4*/Bare et al. (2001), 5*/Kamberis et al. (2000a), 6*/Kamberis et al.(1996), 7*/Kokinou et al.(2005), 8*/Velaj (2015), 9*/Kokkalas et al. (2013), 10*/Underhill (1989), 11*/Karakitsios (1992), T1-6 (Transects 1, 2, 3, 4, 5, 6).

	Sazani Pre-Apulia zone		**Ionian zone**		**Kruja/Gavrovo zone**	
	Albania	**Greece**	**Albania**	**Greece**	**Albania**	**Greece**
Thrusting westwards, on the next more external unit			> 67km (T3 (A)/on Paxos z., 38 km / >47 km (3*, close to the A/H borders)	>21 km (T5, this study) 15.6-19.4 km (7*)	11-13 km up to maximum 18 km (T1)	>20 km (5*) > 10 km (1*)
				15.5-17.7 km (10*) > 53?-58 km (T4, (Ionian thrusting on Apulia)		
Internal Deformation / %		15-25% (10*)	35% (3*), 60% (4*), 44.8% total shortening: W. of Permeti sync. 32.0%, east 12.8% (8*)	40% (3*), 20-30% (11*)	40% (3*), flysch reference horizontal	23% (2*), flysch reference horizontal
Internal (Intrazone) shortening/ km (based on existing data*)			10 km /east of Permeti syncline, 10 -30 km, (Kurveleshi, Cika ant. belt), 20-30 km / Berati belt, (9*, 4*)			
			60 km (5*), 50-60 km (3*)		50-60 (?) km (3*)	
Shortening rate	-	-	2 mm/year (3*, (intrazone deformation)	1mm/y (1*), 1.76 mm/y (6*, T5)	2 mm/year (3*)	1 mm/year (1*)
Detachment nature	Not known-Triasssic evaporites ? (8*)	Triassic evaporites (T5, 7*, this study)	Triassic evaporites (Ionian z), Oligocene (Apulia z.) (T4), Apulia / Ionian z. (T3, T4)	Triassic evaporites (Ionian z), Oligocene (Apulia z.), (T4), Triassic evaporites / Paleozoic (T5)	Flysch / and Mesozoic series locally (Ionian z.)	Flysch-Ionian z.
			Flysch (T1, internal deformation) evaporites (T1, main detachment)			
Detachment depth/sea l. reference	0-10 km (T4)	5-8 km (T5)	10->22 km (T1), 0 up to more than 9 km (T3)	0->12 km (T4), 5-12 km (T5)	0 to 12-13 km (T1)	4.5-8 km (5*/Skolis Mt.)
		10-11 km (9*)		3.5-7.4 km (7*)		

Stack. rock-units thickness		7.5-8 km (T5)	>22km (T1) 9.8+3? km (T3)	>12 km (T4)		13 km (T5)
Structural style	Imbricate (3*, T4)	Imbricate (9*, 7*) + duplex? (4*)	Imbricate/duplex (T4) triplex (T1)	Imbricate/duplex (T4, T5, 8*, 6*)	Imbricate (T1, T4)	Imbricate (T4, T5)
Deformation pattern	Thin-skinned	Thin-skinned (9*, 7*)	Thin-skinned (9*)	Thin/thick-skinned (T5, 9*)	Thin-skinned	Thin-skinned
		Thin/thick ? skinned (T5)		thin-skinned (1*, 3*, 7*)		

Table 3: Petroleum system of the Ionian zone (A/H) and related parameters (Source rocks-lithology, TOC %, porosity %). Data with asterisk (*) are from various works (Diamanti et al., 1995; Gjika et al., 2001; Prifti and Muska, 2010; Velaj, 2015 **; Karakitsios, 2013 ***; Karakitsios and Rigakis, 2007). See also the source map at the end of this work.

Age	**Lithology / source rocks**	**Sample location**	**TOC (%)**		**Porosity % (effective)**	
			A(*)	H (**)	A(*) Fracture/ matrix+vuggy	H(***) (average total)
Eocene - U. Cretaceous	Organogenic limestone			1-28.87	0.1-1.5 0.7-4.2	3
L. Cretaceous	Dolom/shale/Vigla shale member	Outcrop/ well	0.02-27	0.94-5.00	0.1-0.3 1.5-2.3	1.7
U. Jurassic	Shale	outcrop	0.03-509			5*
M. Jurassic	Shale	outcrop	0.04-9.4		0.1-0.3	3
	Clay Limestone with filaments Ammoniticorosso	well	2			3*
U. Toarcian	Posidonia shale	outcrop		1.05-3.34		5
L. Toarcian	Posidonia shale	outcrop	0.09-3.7	1.05-19.12		5
L. Jurassic	Dolomite shale Siniais / Louroslimestone Pantokrator	outcrop	0.01-52		0.5-3.0 1.0-7.0	2* 3* 10*
U. Triassic Lower Triassic	Shale/clay/ Foustapidima limestone ………….. Breccias/dolomite	outcrop	0.02-38.5	16.12	 0.5-3.0 1.0-7.0	3* 13*

Table 4: Proven and potential hydrocarbon reservoirs, traps and seals in Western Greece and the Albanides (Fleury, 1980; Kamberis; 1987; Flores et al., 1991; Albetrol, 1993; Sotiropoulos et al., 2003; Roure et al., 2004; Kokinou et al., 2005; Kamberis et al., 2005; Karakitsios and Rigakis, 2007; Velaj, 2015).

Ionian Zone	**Fields, oil-gas well**	**Oil (O)/Gas(G)**	**Type of trap**	**Potential cap-rocks**	**leads/depth (km)**
1. Upper Cretaceous - Eocene carbonate					
1.1 Overthrust					
1.1.a. Upper Cretaceous - Eocene carbonates/ calciturbidites	Kucove - Finiq - Krane - Cakran – Visoka (A)	O	Thrust related anticline / synclines	Flysch - Neogene clastics	W. Katakolo field/2540 m/(H)
				Diapirism of Triasic evaporites	(H)
				Neogene clastics (Patos, Marinez, Ardenica)	3-4 medium depth (A)
	Delvina - Shpiragu – Karbunara (A)	O	Subthrust related hanging wall anticlines (duplex deform. pattern)	Flysch + evaporites (Memalija syncl.)	5-6 (A)
1.1.b Flysch - sand levels	Synclines (A): Memaliaj discoveries /Dumre-7 well, Kucove		Thrust related hanging anticlines/ synclines (subsalt structures)	Triassic evaporites	Kucove fields >1000 m, Dumre-7 well, 6 km, Permeti syncline, 2.5-3 km (A)
	Episkopi - Kucove, Patos-Marinez (A)	O	Thrust related anticlines / intraformation (flysch) imbricates	Flysch/Neogene clastics	< 2 km Kucove, 3 km Patos-Marinez (A)
1.2. Subthrust					
2. Neogene sedimentary sequences	no data		Probably stratigraphic, tectonic structures		
2.a. Peri-Adriatic depression	Ballaj				
Pliocene turbidites-sands	Divjaca (A)	G	Backthrust related traps (flower structure)	Neogene clastics	2 km (Pliocene leads) (A)
Upper Miocene sands	Patos-Marinez-Pekisht (A)	O	stratigraphic		2-4 km
2.b. Middle Miocene/ Tortonian-Messinian sands	Patos-Marinez-Pekisht (A)	O	stratigraphic traps / stratigraphic related to unconformity		
2.c. Tortonian - Messinian sands	Divjaka, Povelca, Panaja,	G	Tectonic structures,	Neogene clastics	<2 (A)

	Frakulla, Durres (A)		culminations stratigraphic		
2.d. Tortonian-Messinian sands	Kucove (A)	O	Stratigraphic (sand horizons)	Pliocene clastic sequences	<1 (A)
Kucove					
1.2. Beneath the overthrust of the External zones (Ionian, Gavrovo)	Potential reservoir rocks	O	Thrust related aniclines/synclines (transect 4/A/H)	Thrust equivalent deposits in flysch + Triassic evaporites	>4,5-6,5 (A)
1.2.a. Upper Cretaceous-Eocene calciturbidites	Possible gas/oil fields	G	Culminations		>5,5 (H) (transect 5)
	limited exploration/drillings/ future exploration				>6 (Peri-Adriatic depression)
Gavrovo zone					transect 1
1.1. Paleogene / Eocene overthrust	Potential reservoir rocks		Thrust related anticlines (East of Scolis Mt./ (H)	flysch (A/H)	>2-3/W. Greece Skolis/W. Aetoloakarnania (H)
1.1.a. Carbonates organogenic	Gas prone/outcrops				
	Impregnations of oil (Filiatra-1 well/NW Peloponnese)				
1.1.b. Upper Cretaceous carbonates	No well data (A)		Stratigraphic related to unconformities (i.e. between Molasse and Carbonate/Visoke field-type)	Molasse	Limited exploration/no significant results from drillings (A/H)/Aetoloakarnania, Apollon-1 /East of Skolis Mt) (H)
1.1.c. Flysch	Sandstones		Stratigraphic (A/H)	Flysch (repeated slices) + Molasse (A)	No data
Pre-Apulia					
1.1. Overthrust (transect 5)					
1.1.a. Jurassic and Cretaceous carbonate	Potential reservoirs rocks (A) ?		Thrust related anticlines (Paxos-1 well) broad, large scale structures	Marly limestones /marles	Medium to deep leads (>5 km/Zakynthos-1, Paxos-1 wells)/ transect 5
1.1.b. Miocene/Pliocene deposits	No data		Stratigraphic/tectonic potential traps		3-5 (?) Zakynthos Isl. channel

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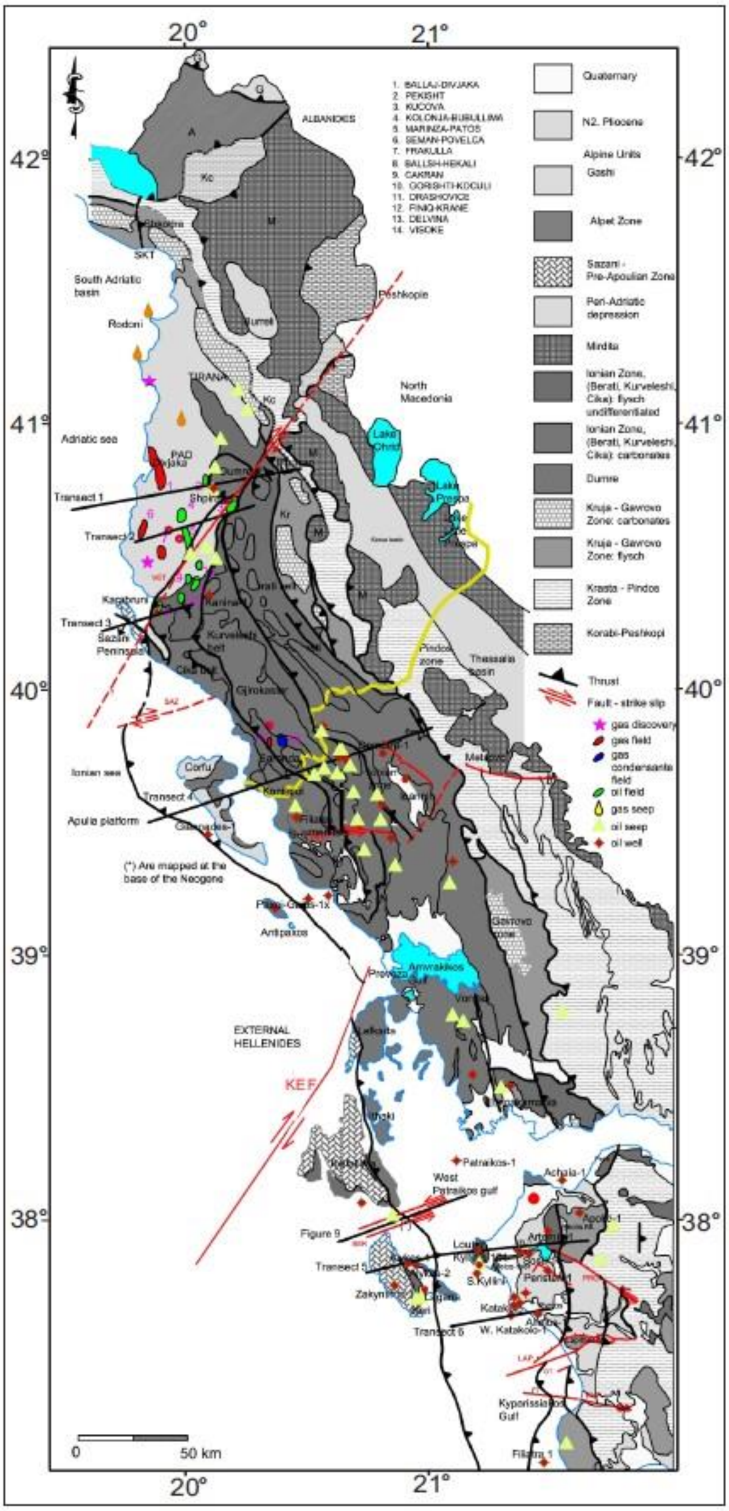

Figure 1: Geological map of the study area based on the Geological map of Greece 1:500.000, (IGME; ISPGJ-IGJN, 1983, 1985; Kamberis, 1987, 1992, Zelilidis et al., 2003; Karakitsios and Rigakis, 2007; Karakitsios, 2013; Kokkalas et al., 2013; Velaj, 2001, 2015, this study) and field work in the context of the present study. The locations of the transects are shown in black lines, main tectonic structures (strike-slip faults) in red lines, thrust faults in black lines with triangles.

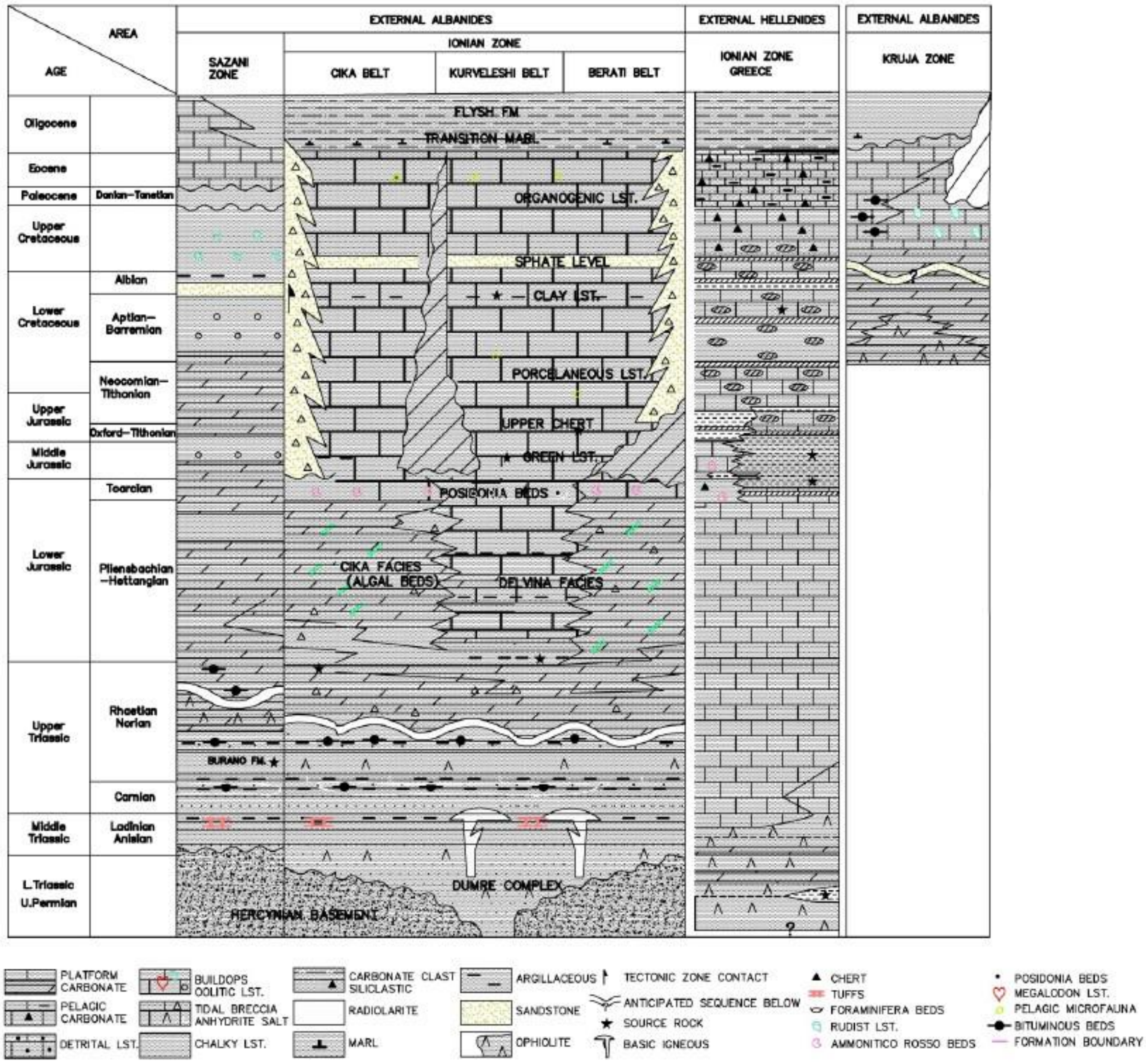

Figure 2: Lithostratigraphic columns of the External Hellenides (H) and Albanides (A). Data for the lithological columns of the External Albanides are from Diamanti et al. (1995), Anglo-Albanian petroleum LTD Western Geophysical publicity brochure (Albpetrol, 1993) and Roure et al. (2004). Data for the External Hellenides are from Monopolis and Bruneton (1982), Roussos and Marnelis (1995) and Karakitsios and Rigakis (2007).

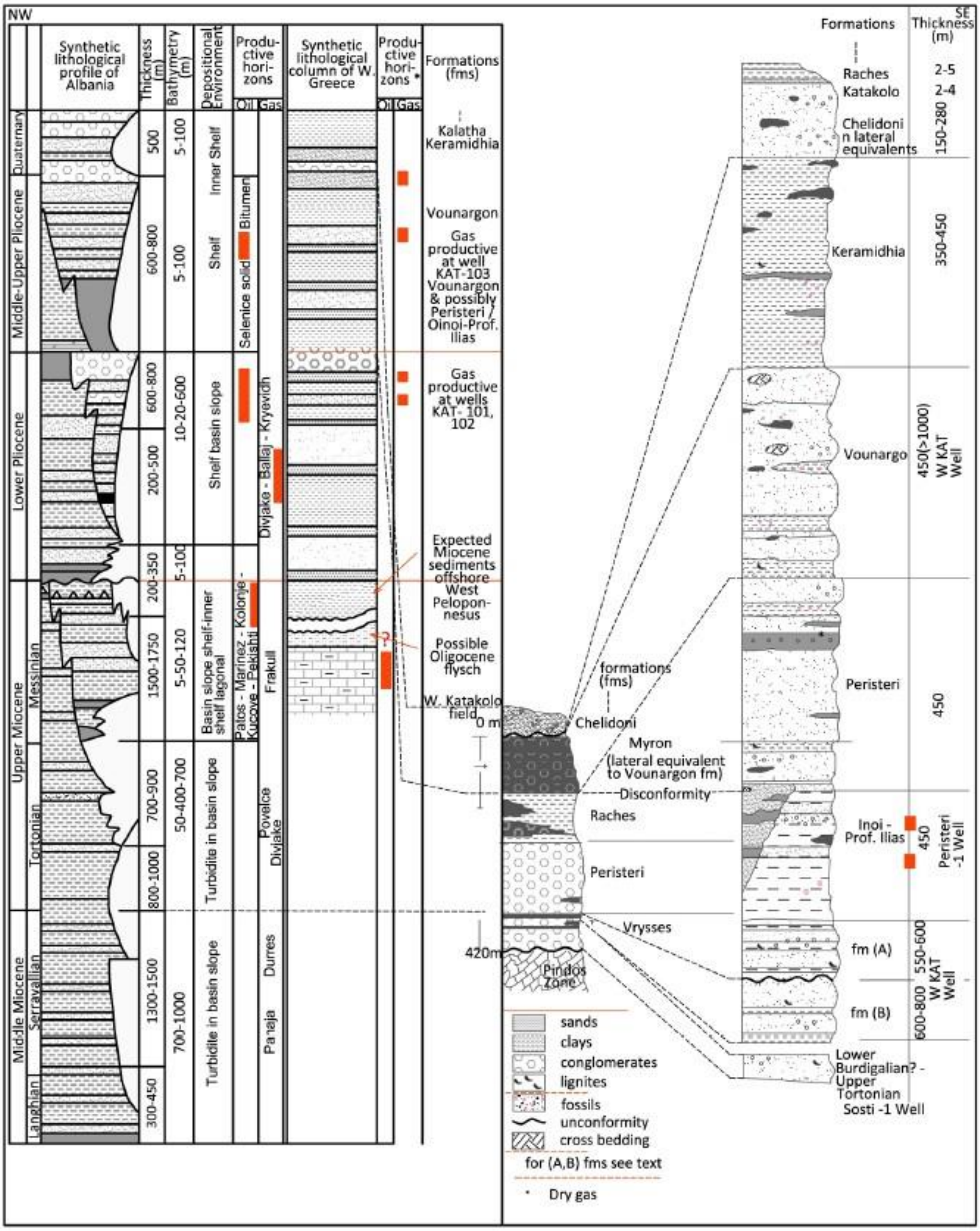

Figure 3: Lithological columns of the Neogene-Pleistocene stratigraphy in Albania and Western Greece. Data for the lithological column of Western Greece are from Kamberis (1987), Kamberis et al. (1992), Kamberis et al. (2000), Roussos and Marnelis (1995) and Mavromatidis et al. (2004). Data for the lithological column of Albania are from Gjika et al. (2001).

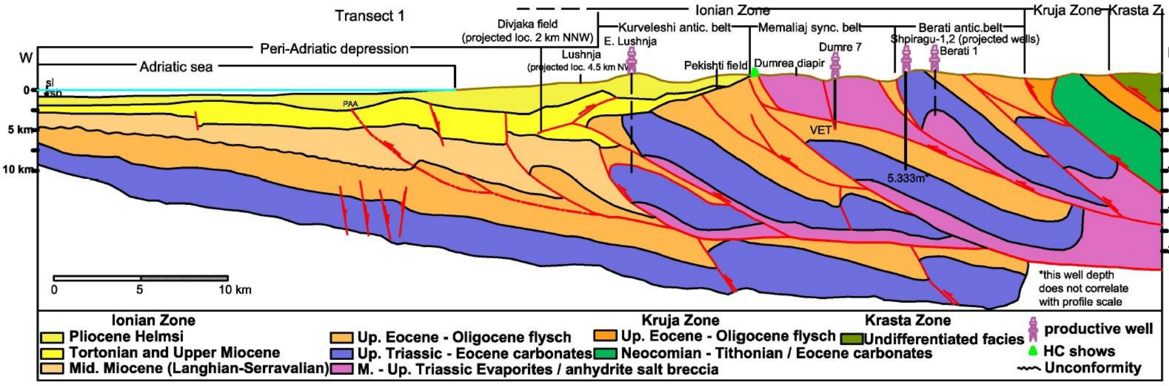

Figure 4: Transect1 (location in Fig. 1) extending from the Peri-Adriatic depression up to Krasta Zone (Velaj, 2015, in part modified and completed in this study). It presents the structure up to depths of more than 20 Km. Prevailing compressional structures in this transect are: a) the boundaries of Ionian-Kruja and Kruja-Krasta zones, b) the boundaries among the belts (Kurveleshi anticline, Memaliaj syncline, Berati anticline) of the Ionian (A) zone and c) smaller scale internal thrusts. Red lines indicate faults while the red arrows show the sense of the faults.

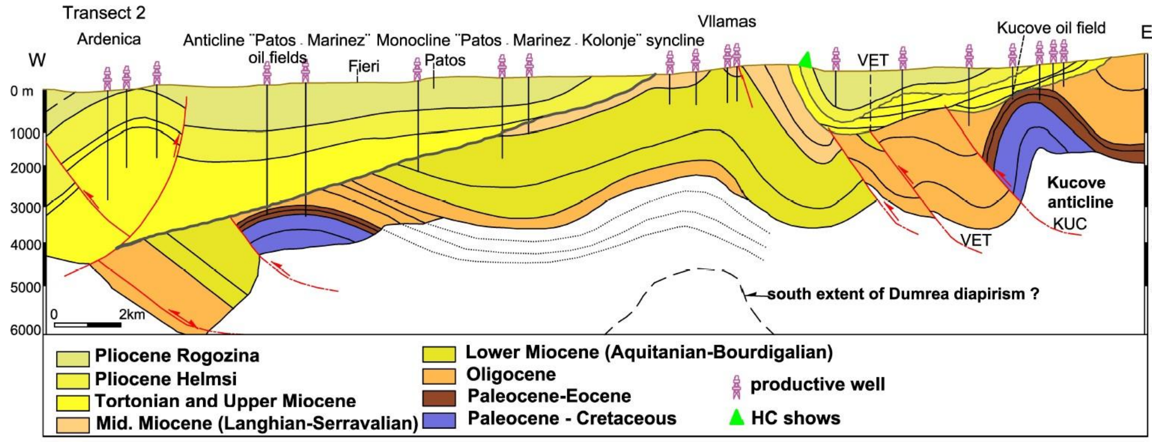

Figure 5: Transect 2 (see location in Fig. 1) based on information from Ardenica-Kucove (Velaj, 2015, in part modified and completed in the present work). It shows the structure up to depths of 6 km. Prevailing tectonic structures from east to west are: a) the Kucove anticline, b) Vllamas anticline, c) the Patos-Marinez-Kolonje monocline, d) the Patos-Marinez anticline that overlies the Vllamas anticline at about 3 km in depth, and e) the Ardenica flower structure associated with thrust and post Early Pliocene ("Helmsi") back-thrust faulting. Out of sequence thrusting in the Shushika syncline belt of the Ionian zone (A) postdates back thrust movements (see the eastern flanks of Cika anticline belt). Red lines indicate faults while the red arrows show the sense of the faults.

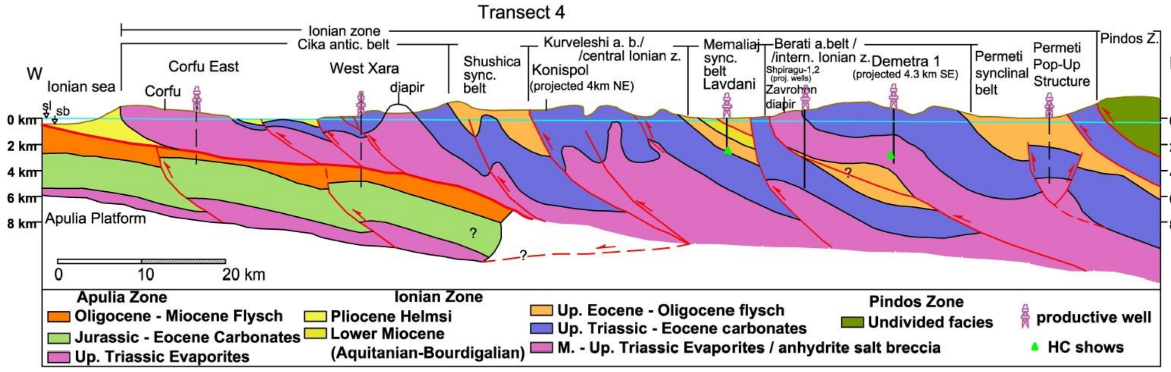

Figure 6: Transect 3 (location in Fig. 1), Karabruni (Apulian Platform)-Kurveleshi anticlinal belt (in Velaj, 2015). It presents the structure up to depths of more than 8 Km. The structural style across this transect is also controlled by compressional deformation (Velaj, 2015) characterised by duplex and complex imbricated nappes type structural pattern and possible out of sequence thrust-fault activity (Shushika synclinal belt) during the post Middle Miocene-Upper Miocene (post Tortonian ?) times. Red lines indicate faults while the red arrows show the sense of the faults.

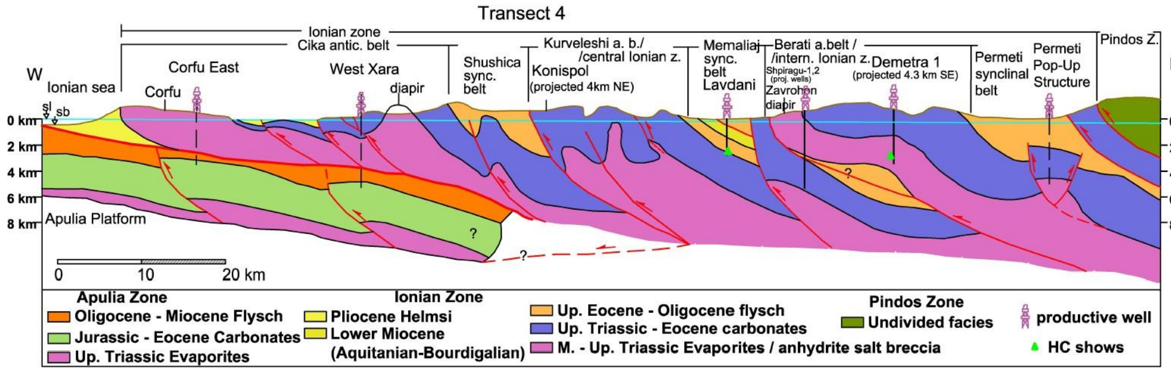

Figure 7: a) Transect 4 (location in Fig. 1), Corfu-Permeti (Velaj, 2015, in part modified and completed in the present work) showing the structure up to depths of 8 Km. Prevailing compressional structures from east to west are: 1. the nappe of Krasta/Pindos zone, and 2. the Ionian zone of Albania (Berati, Kurveleshi and Cika belts). Red lines indicate faults while the red arrows show the sense of the faults. b) restored Transect 4 where the top of Triassic evaporites corresponds to the reference level for the restoration of the Mesozoic -Tertiary units taking into account the significant erosion of the Eocene (and the Tertiary flysch).

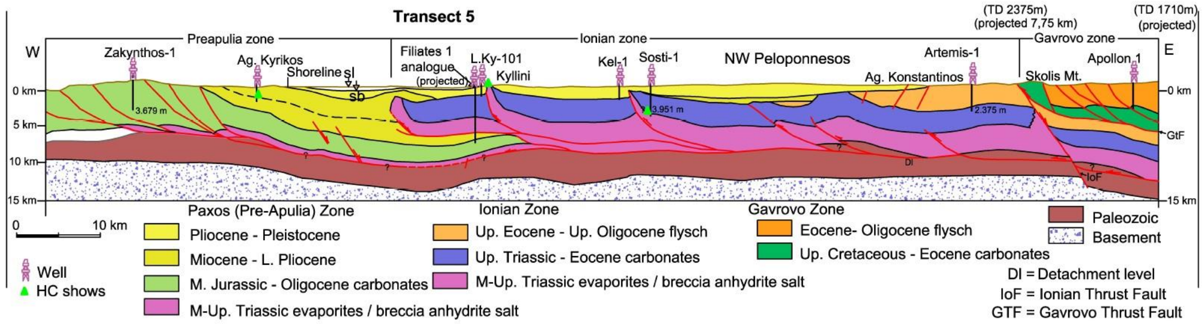

Figure 8: Transect 5 (location in Fig. 1) showing the structure up to 15 Km (based on Kamperis et al., 1996 and partly modified in this study). The Gavrovo, the Ionian and the Pre-Apulia (near Zakynthos Island) zones are present in this transect. Red lines indicate faults while the red arrows show the sense of the faults.

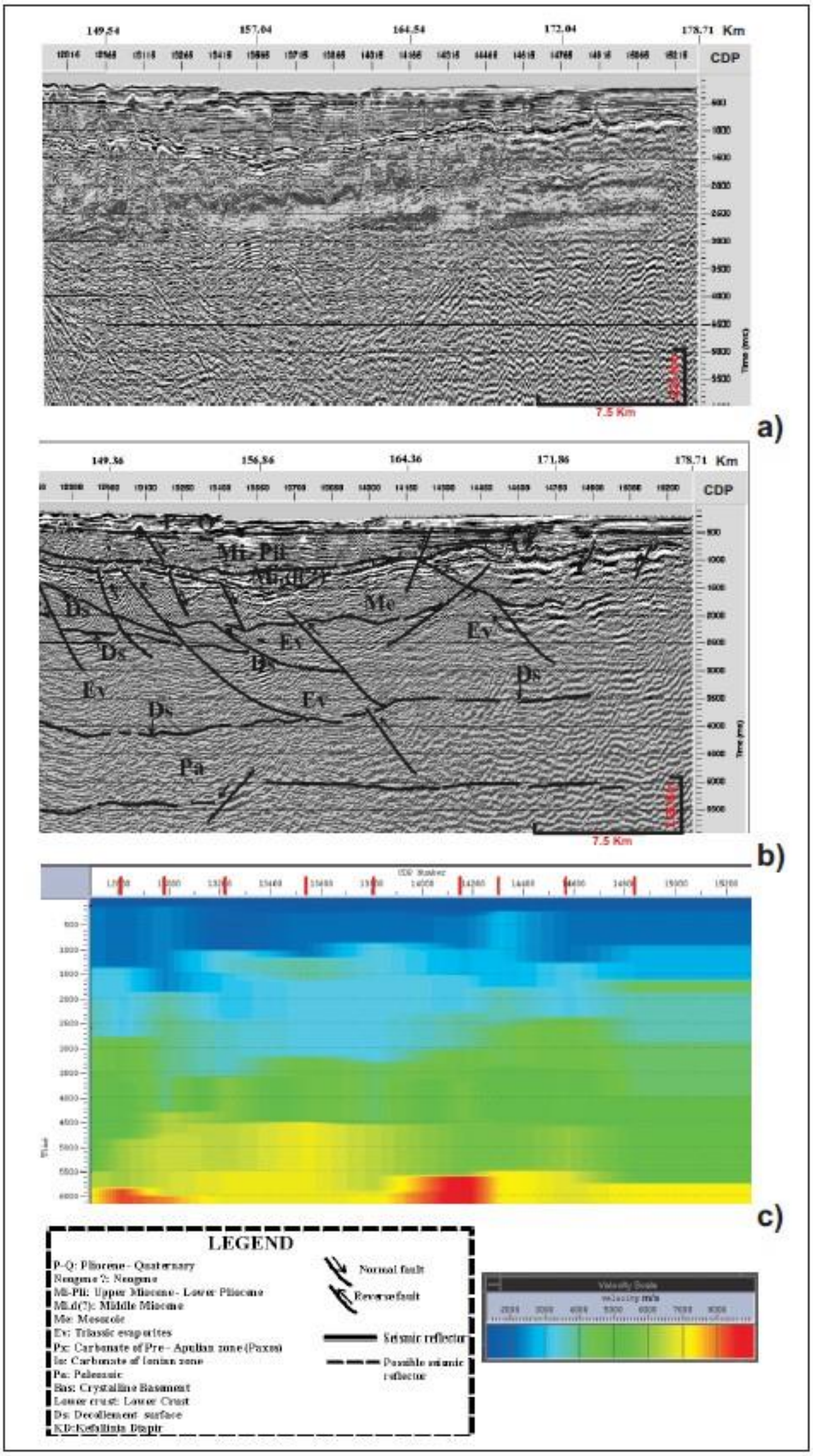

Figure 9: a) Stacked seismic section from ION-7, crossing the offshore area east of Kefallinia and Zakynthos up to the Gulf of Patras (see location in Figure 1), b) the time migrated section (Kokinou et al., 2005), c) seismic velocities corresponding to this part of the stacked section. The Permian-Triassic (pre-evaporite) base of the evaporites corresponds to the lithoseismic layer located between 3.5 and 5.0 sec (TWT).

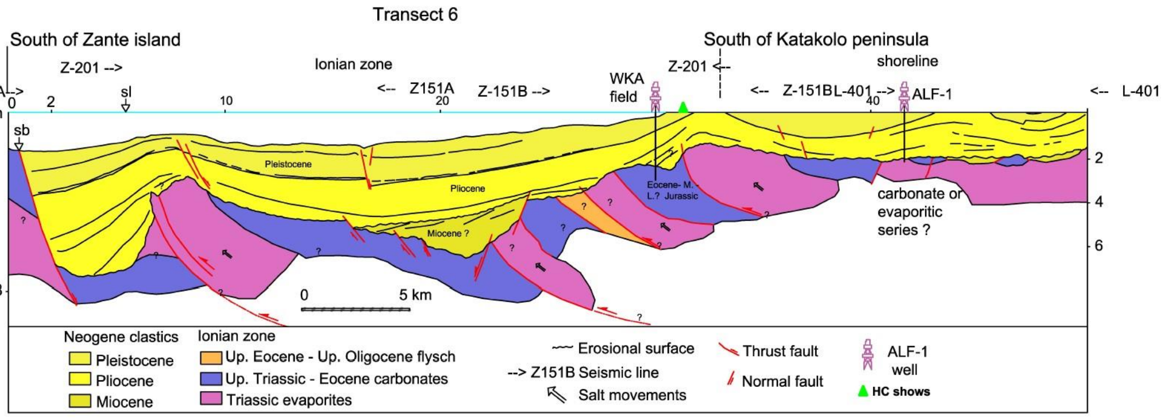

Figure 10: Transect 6 (location in Fig. 1), offshore, Southeast Zakynthos Island-Katakolon peninsula (according to Kamberis et al., 2000b and partly part modified in the present work). It shows the structure up to 8 km. Prevailing structures from east to west are: 1. the thrust fault related repetition of Triassic evaporites/carbonate units with imbricate/duplex type of compressional structures (Ionian zone), and 2. the normal fault of regional scale bounding the westernmost part of this transect. Red lines indicate faults while the red arrows show the sense of the faults.

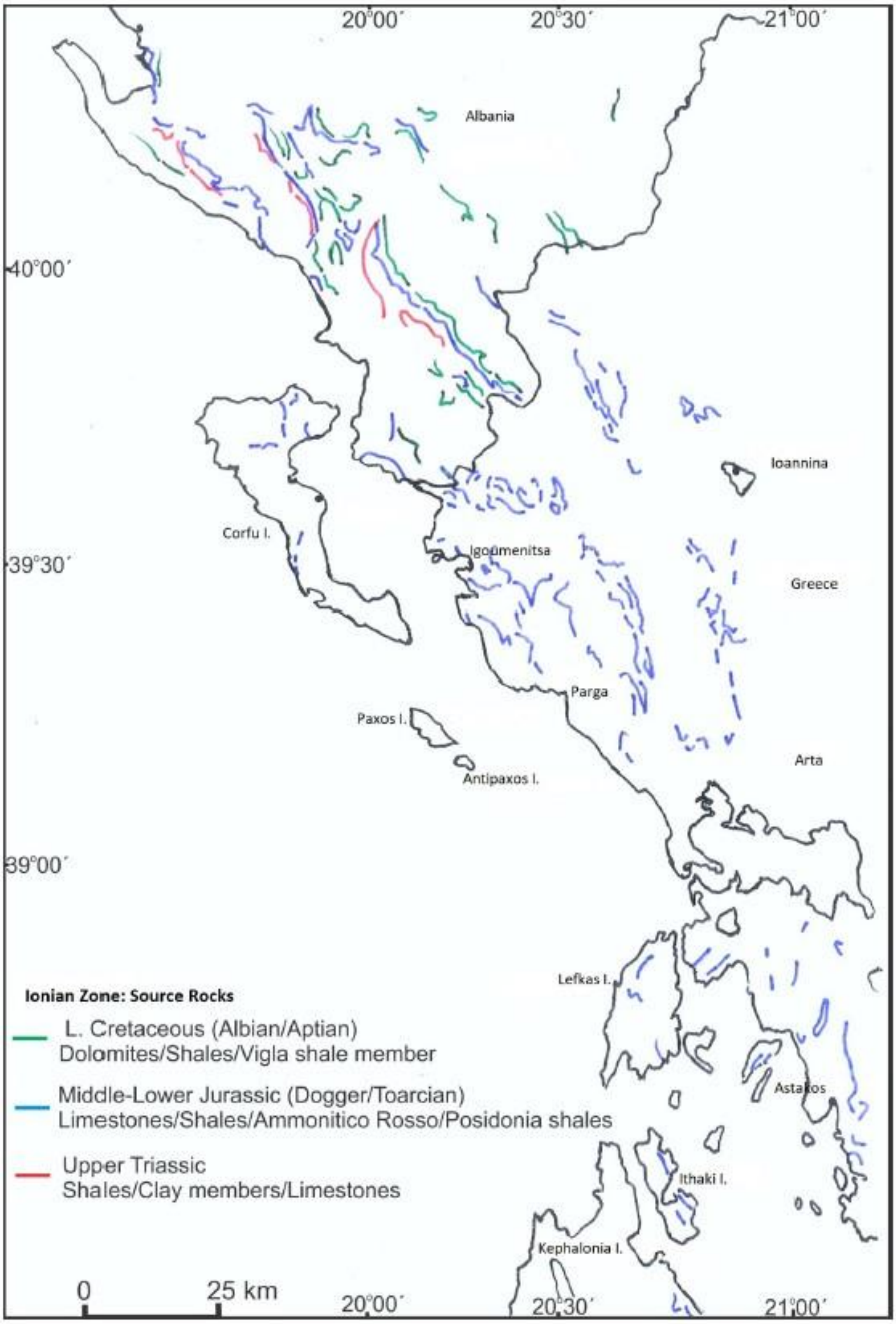

Figure 11: Distribution of the main source rocks outcropping in the Ionian Zone in Western Greece and Southwestern Albania, based on previous information (IGRS-IFP, 1966; 1:500.000, IGME, 1983, Geological map of Hellas after Bornovas and Rondogianni-Tsiambaou) and field work implemented in the context of the present study.

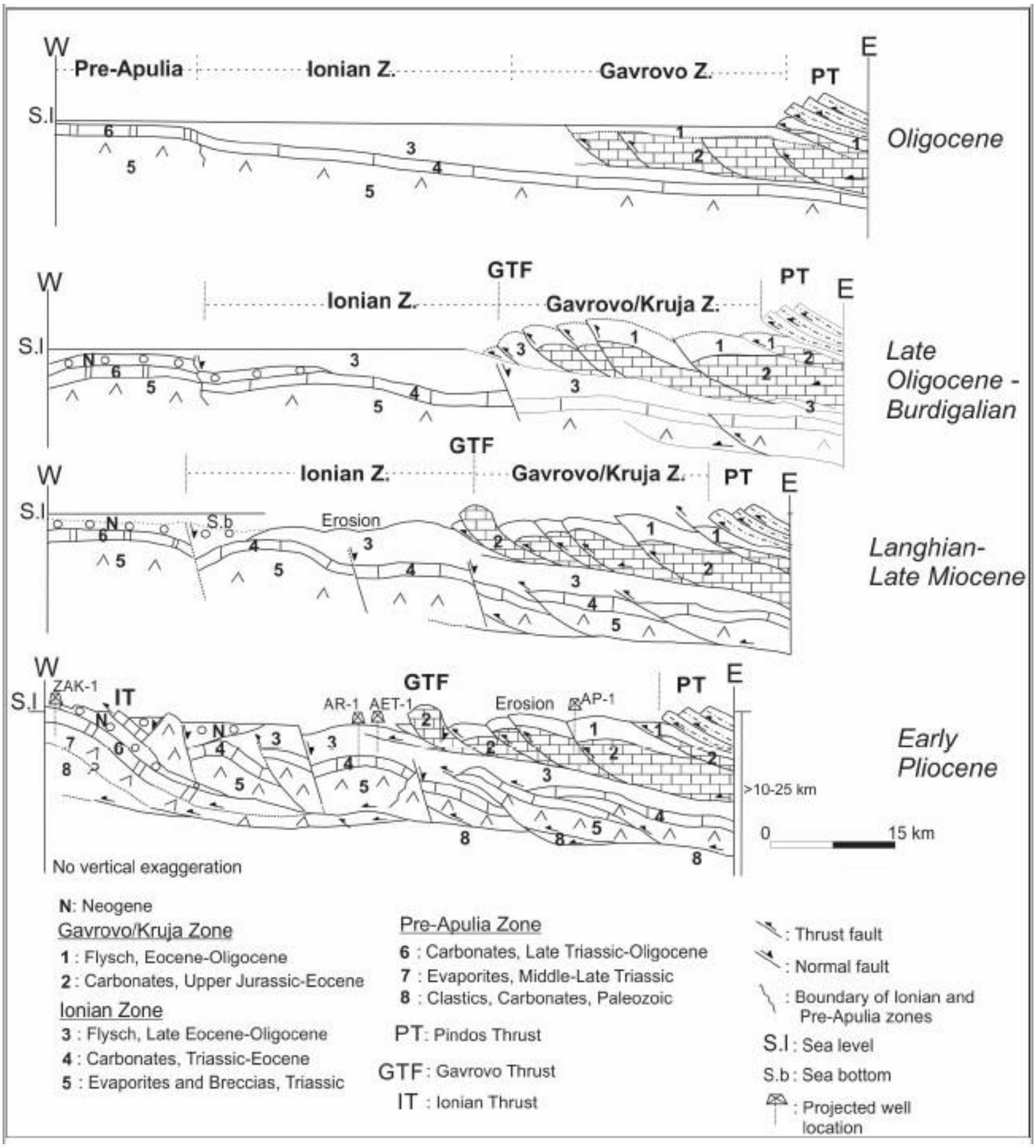

Figure 12: Schematic cross sections showing the evolution of the External Hellenides – Southern Albanides thrust- and fold belt. Location of the wells in Figure 1, AR-1: Artemis-1, AET-1: Aetolikon-1, AP-1: Apollon-1, ZAK-1: Zakynthos-1. The vertical scale is indicative.