SEISMOTECTONICS OF THE ALBANIDES COLLISION ZONE: GEOMETRY OF THE UNDERTHRUSTING ADRIA MICROPLATE BENEATH THE ALBANIDES

Shyqyri ALIAJ
Retired from Institute of Seismology, Academy of Sciences of Albania

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ABSTRACT

The present-day tectonics of the Albanides continental collision zone was investigated and the geometry of the main Albanides thrust was quantified based on the fault plane solutions for the November 26, 2019 Mw 6.4 Durres earthquake and other earthquakes events in Albanides collision zone. Here, the inferred geological and geophysical (seismic and gravimetric) data for the Albanides, and separately for the Periadriatic Foredeep Basin were also used. The Albanides collision zone is situated in an area lying between the Adria-Albanides collision thrust and Kruja nappe front. The Albanides-Adria collision thrust is divided into the north-west trending Lefkas-Corfu, and the generally north-south trending Dhermi-Durres segments through the Dhermi-Othoni Island dextral transfer fault. In the seismic and geological cross sections passing through Ardenica and Durresi hills two structural stories could be distinguished: an upper story or 'superstructure' which shows the tête à tête Adria-Albanides collision, and a lower story or 'infrastructure' that shows deep Earth crust part of the Adriatic block. Both the fault plane solutions determined by various agencies for the November 26, 20919 earthquake and the focal plane solutions determined by GFZ for main shock and two aftershocks of magnitude greater than 5 of the November 26, 20919 earthquake show that they occurred on the NNW-SSE striking frontal blind thrust of low-angle dipping towards the east, locating on the main basal thrust separating the Adria microplate underthrusting beneath the Albanides that is called the main Albanides thrust (MAT). The November 26, 2019 Mw 6.4 Durres earthquake ruptured the MAT by highlighting its ramp and flat geometry. The fault geometry of the MAT consists of the following portions: i) the tête à tête Adria block backthrust to the Albanides frontal blind thrust fault, followed by ii) a flat (10-15^{o}) co-seismic décollement surface northeast dipping, that ends on a iii) 20-25^{o} mid-crustal ramp that intersects iv) a wide northeast gently dipping that gradually passes into a sub-horizontal section of aseismic (creep) deformation. The MAT shows the double-ramp geometry with a flat detachment in between. Durresi hill - Korabi Mt, and Ardenica hill - Dumre diapir - Skenderbeu village - North Macedonia border geological cross sections crossing the Albanian Basin and Mali i Kanalit Mt - Mali i Thatë Mt geological cross section crossing the Apulian platform show the fault geometry of MAT. MAT geological cross sections show that Albanides nappe pile can be divided into these two plates: i) the Ionian fold-and-thrust basal nappe, affected by reverse faulting comprising the Albanides collision zone in compression, constitutes the lower plate, and ii) the Kruja nappe and overlying nappes, affected by normal faulting comprising the internal domain in extension, form the upper plate. Deformation of orogenic crust at Albanides during Tertiary occurred and occurs into both plate levels: i) a basal fold-and-thrust system in the Ionian Zone, that accommodated an increasing amount of SW directed shortening, and ii) a structurally higher system of normal faulting affecting the Kruja nappe and overlying ones, that underwent a strong structural rearrangement. Present-day convergence across the Albanides is mostly accommodated along the MAT.

Keywords: November 26, 2019 Durres earthquake, Albanides continental collision zone, seismotectonics, fault plane solutions, Main Albanides Thrust

1. INTRODUCTION

This paper aims to model the deep Earth's structure of the Albanides fold and the thrust belt, which is an orogenic wedge formed by a stack of nappe sheets scrapped off Adriatic continental crust as it was underthrusted beneath the margin of Eurasia after closing of the Tethyan Ocean.

The fault geometry of the Adria Microplate underthrusting beneath the Albanides has been investigated based on the fault plane solutions of the November 26, 2019 Mw 6.4 Durres earthquake and other earthquakes events Albanides collision zone and on the geological background for the Albanides and separately for the Periadriatic Foredeep Basin is investigated the fault geometry of the Adria Microplate underthrusting beneath the Albanides. The Albanides collision zone is the seismic source zone of the September 21, 2019 Mw 5.6 and the November 26, 2019 Mw 6.4 Durres earthquakes and of coastal strongest earthquakes in Albania.

The Albanides is divided into the external collision domain in compression characterized by the reverse faulting, and the internal extensional domain characterized by the normal faulting. The Albanides (frontal part of the Eurasian Plate) collides with the Adria microplate that is fragmented into these two subplates: the Apulian platform from Sazani Island to the south, and the Albanian basin (=South Adriatic basin) to the north of it (Aliaj 1998; Aliaj *et al.*, 2018).

Aliaj and Kodra (2016) discussed the Albanides setting and proposed to put them into the segment between the Shkoder-Peja and Sperchios (Kremasta-Sperchios) transform-faults comprising a big folded segment with the same tectono-stratigraphic units in Albania and Greece. This is also here discussed.

The convergent boundary between the Albanides and Adria Microplate is now well constrained to be located in the Adriatic and Ionian coasts. The inferred and reviewed geological data show that the Albanides frontal thrust, cut and displaced by the southwest-northeast extending Lezha-Drini Bay and Dhermi-Othoni Island dextral transfer faults, is divided into the generally north-south trending Dhermi-Durres segment and the north-west trending Lefkas-Corfu segment.

The Dhermi-Durres thrust investigated in details follows the contact between Sazani and Ionian tectonic units up to Vlora city and then from Panaja through Frakulla to Durresi anticlinal line of quasi-northern extension it is deeply buried under Middle Miocene molasses of the Periadriatic Foredeep basin.

The main characteristics of the September 21, 2019 Mw 5.6, and the November 26, 2019 Mw 6.4 Durres earthquakes

The forthcoming paragraphs briefly describe the main characteristics of the September 21, 2019 Mw 5.6 and the November 26, 2019 Mw 6.4 Durres earthquakes. There are two newsletters of Environmental, Disaster, and Crises Management Strategies: Issue No 13 for the September 21, 2019 Mw 5.6 Durres (Albania) earthquake (Lekkas *et al*., 2019) and Issue No 15 for the November 26, 2019 Mw 6.4 Durres (Albania) earthquake (Lekkas *et al*., 2019) describing these two evets.

On September 21, 2019, the Durresi-Tirana area was hit at 14 h 04 min by a Mw 5.6 Durres earthquake. Its focal depth is estimated 20 km and the epicenter located 5 km north of Durres city (41.37N 19.45 E) (EMSC). This earthquake was felt on a large territory of our country. One hundred and five people injured, 1528 buildings were damaged and 50 dwell houses were totally collapsed. An aftershock sequence followed the main shock: 9 aftershocks on September 21, 2019 (3 of magnitude M = 5.1, 4.7 and 4.8; and 6 of M = 3.0-3.4), 13 aftershocks on September 22 (2 of magnitude M = 4.4, 4 of M = 3.3-3.5 and 9 of M = 2.1-2.9), and only 2 aftershocks on September 23, 2019. After 5 first days the aftershocks of M > 2.0 are increased. The focal dimensions of the November 26, 2019 Durres earthquake calculated from spatial distribution of its aftershocks M ≥ 3.0 report the following characteristics, as depicted in the Figure 1: the length 30 km and the width 20 km.

The figures 1- 3 depict the reverse faults in coastal part of the country. The different colors show chronologically the activity: Blue lines show faults activated during Middle Pleistocene-Holocene or Quaternary, green lines faults activated during Pliocene-Lower Pleistocene or Pliocene-Quaternary, and red lines faults activated during pre-Pliocene, active maybe during Pliocene-Quaternary (Aliaj *et al*., 1996; 2018).

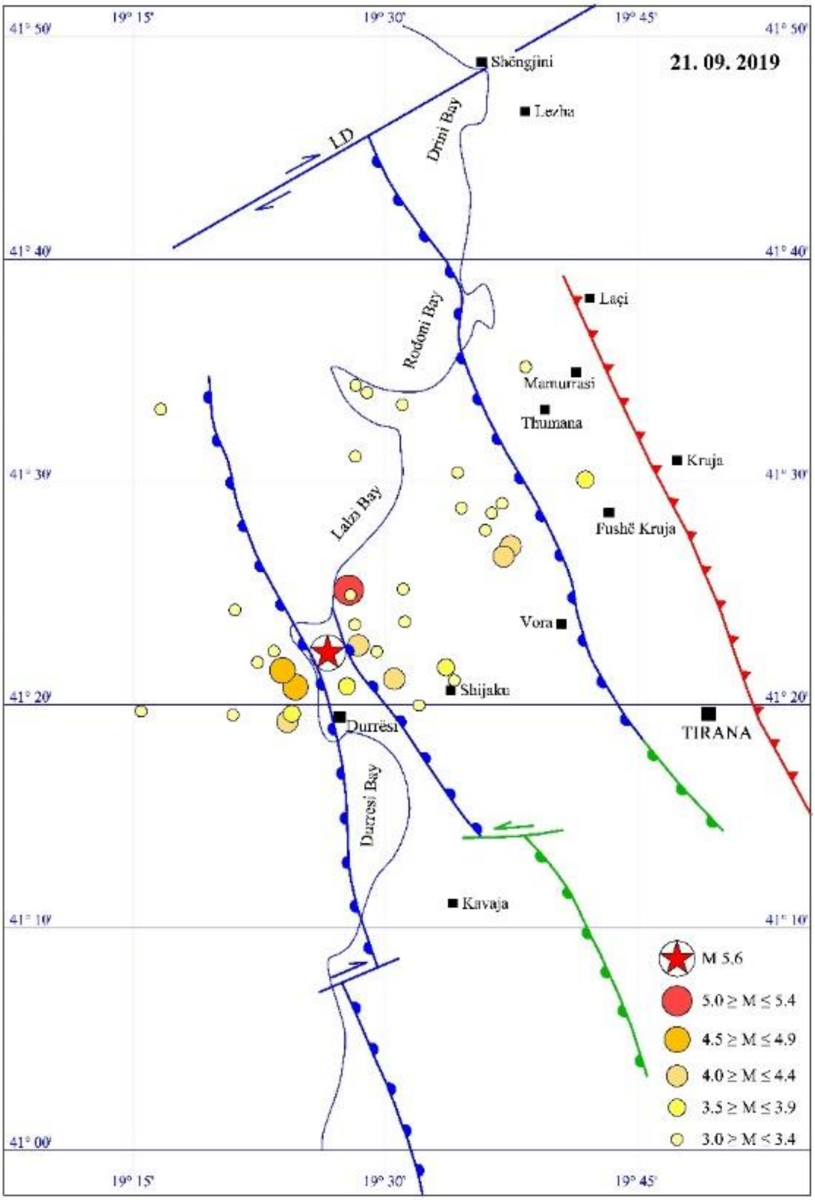

Fig. 1: Map of aftershock sequence of the September 21, 2019 earthquake Mw 5.6 (EMSC data).

On November 26, 2019 Mw 6.4 Durres earthquake at 02h 54 min (GMT) struck the Durres City and a large coastal area. The epicenter located 7 km north of Durres City (41.38 N 19.47 E) and focal depth estimated 10 km (EMSC). Its seismic intensity IX degrees MSK-64 scale is estimated based on the general panic associated with the hard stress in population of the large heavy damaged Durres-Tirane-Thumana area and on liquefaction phenomena observed in Durres beach, Jub-Sukth, Rrushkull and Fushe-Kuqe areas near to the epicenter of the November 26, 2019 Durres earthquake. The maximal perceived intensity was VIII (severe) on the Modified Mercalli intensity scale.

The main shock was felt in Montenegro, Kosova, Italy and Greece. This earthquake caused 51 casualties, 900 injured and 17000 people were left homeless. Durresi and Thumana were heavily damaged, with many residential buildings and hotels were totally collapsed. One thousand, one hundred and eighty-three 1183 houses collapsed and other 5497 houses were heavily damaged.

Pavlides *et al*., (2019) described in details the ground effects of the November 26, 2019 earthquake in Durres beach, Rrushkull and Fushe-Kuqe areas. The widespread liquefaction together with lateral spreading along the river banks on Rrushkull area observed along cracks parallel to the river banks having a general trend NE-SW, while the longest one shows a rather uniform displacement vector towards the NW. In addition, Pavlides *et al*., (2019) said that a small displacement of up to 15 cm was also evident in some cases along the cracks. A crack zone composed by two parallel cracks of 10-20-50 cm up to 1 m width prolonged for some hundred meters we observed in Jub-Sukth nearby to Erzeni river mouth, where a westward lowering displacement up to 10-20 cm along the cracks is evidenced (Allkja *et al*., 2019).

The November 26, 2019 Mw6.4 Durres earthquake was preceded by two foreshocks among which the strongest one M4.9 occurred at 01h 47min (GMT). The main shock of November 26, 2019 Durres earthquake was associated by a long aftershock sequence. On January 29, 2020, the last strongest aftershock M4.9 occurred in the Adriatic offshore, but the aftershock sequence extended for about 3 months till the mid-February 2020 with magnitude more than 3.0. The aftershock sequence includes 4 aftershock M = 5.1-5.4 (3 on November 26 and 1 on November 27, 2019), 28 aftershocks M = 4.0- 4.9 (18 on 3 first days, 8 from November 29 to December 19, 2019 and only 2 aftershocks on January 28, 2020) and 150 aftershocks M = 3.0-3.9 (60 aftershocks on 3 first days). Some thousand aftershocks M< 3.0 occurred too (IGJEUM).

The strong November 26, 2019 Mw 6.4 Durres earthquake occurred on the collision frontal thrust of the Albanides orogeny. The focal dimensions of November 26, 2019 Durres earthquake calculated from spatial distribution of the aftershocks M ≥ 4.0 are: the length 30 km and the width 20 km (Figure 2), while of the aftershocks M ≥ 3.0 are: the length 40 km and the width 30 km (Figure 3).

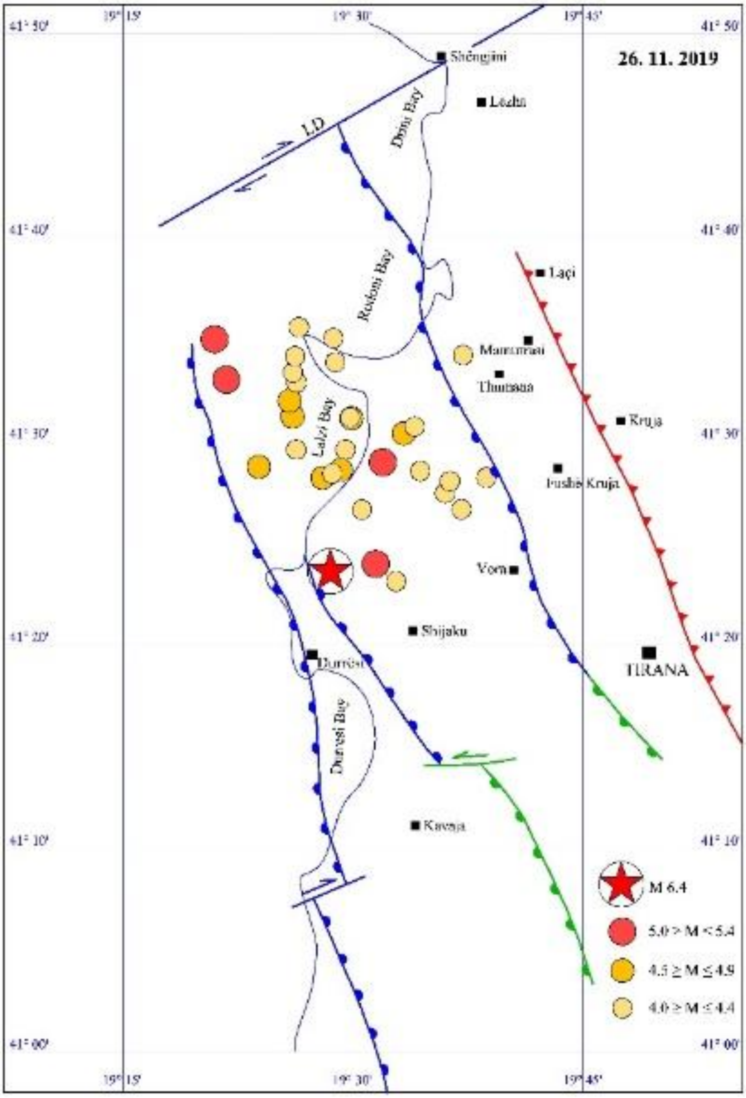

Fig.2: Map of M≥4.0 aftershocks of earthquake of November 26, 2019 Mw 6.4 (EMSC data).

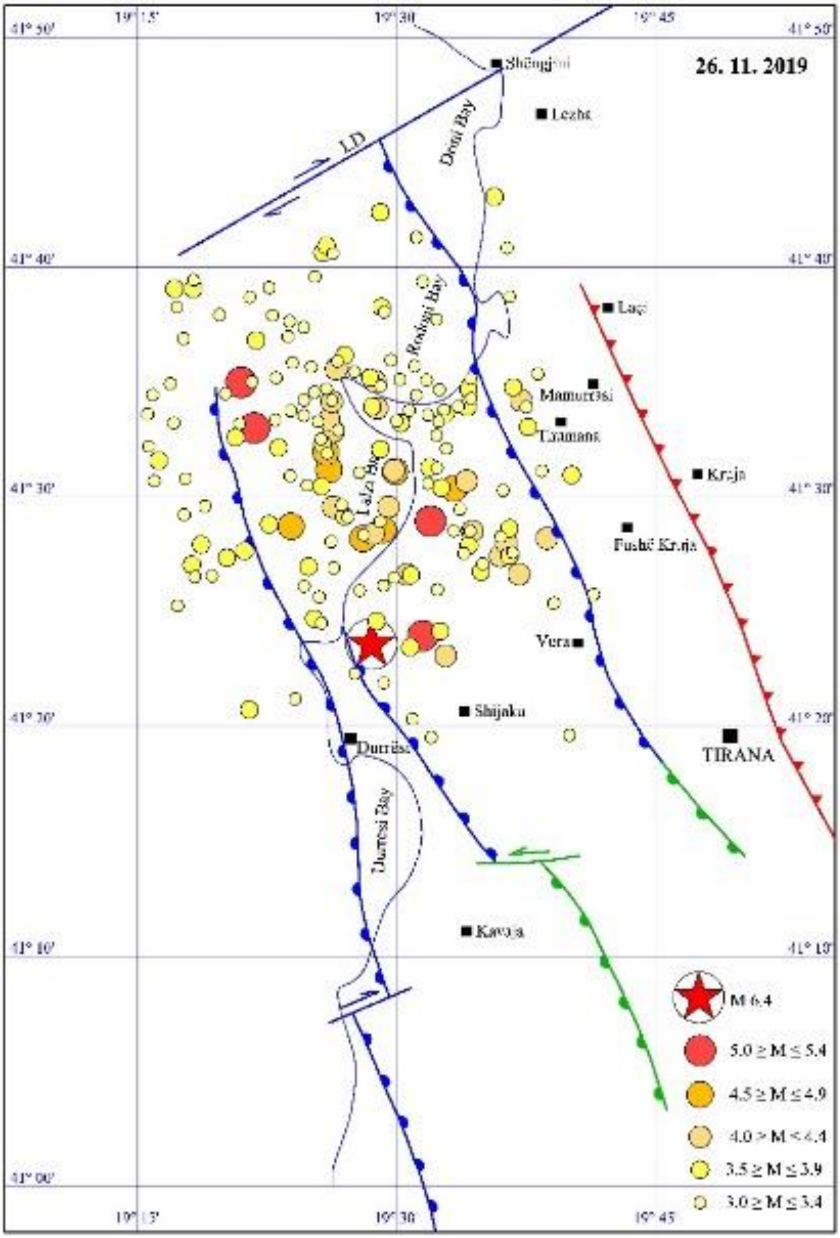

Fig. 3: Map of M≥3.0 aftershock sequence of earthquake of November 26, 2019 Mw 6.4 (EMSC data).

The vertical movements induced by the November 26, 2019 Durres earthquake are measured by Sentinel-1 satellite of European Space Agency (ESA) through the interferometer radar technique. An inSAR data (CGG 2019) shows that the November 26, 2019 earthquake produced the uplifting of tectonic origin up to 10 cm near Durres, and 8.4 cm at Hamallaj village, 15 km east of Durres, while far away, towards the east subsiding reaches up to 10 cm which is a good evidence to the westward movements of Albanides over the underthrusting Adria Microplate. The strong deformation of north-south trending Durres-Rodoni Bay area (Grandin 2019) identifies the heavy damaged Durres-Thumana area of VIII-IX intensity degrees.

The Durres accelerometric station shifted southwestwards at least 5.4 cm and uplifted 1.2 cm (Duni and Theodoulidis 2019). DUR2 GPS indicates a displacement of 11 mm west, 17 mm south and 15 mm up (Moshu *et al.*, 2019). They demonstrate the southwestward motion of the overriding Albanides (frontal part of Eurasian Plate) over the Adria microplate underthrusting.

Geological background of the Albanides fold and thrust belt

The Albanides fold and thrust belt is formed after closuring of the Mesozoic Tethys Ocean by the subduction of the Adriatic continental lithosphere beneath the Eurasian plate since the Eocene-Oligocene times**.**

Structural evolution, geometry and kinematics of the Albanian nappe pile during the Tertiary are envisaged by Kilias et al. (2001). All the external zones are included into the low plate, while the internal units of the Korabi with Mirdita one on its top in the upper plate. Four main sets of structures due to D_1-D_4 deformational events during Tertiary have been distinguished. The D_4 high angle normal fault event strongly modified from the Miocene onwards the pre-existing deformation geometry of the Albanides.

Aliaj and Bushati (2019) pointed out that the outcroppings of huge ultrabasic bodies beneath the Korabi nappe indicate the Mirdita Zone ophiolites roots. The Mirdita zone includes the ophiolites with their sedimentary cover and their boundary with Korabi zone passes after the eastern margin of the ophiolite massifs, which follows from Kukës-Peshkopi region in the north to Mali i Thatë Mountain in the south. The Korabi zone is characterized by a Paleozoic basement consisting of the Ordovician to Devonian sequence unconformably covered by a Permo-Triassic clastic sequence grading upward to Triassic-Jurassic carbonate sequence. The Korabi units are deformed in a large antiform showing at its core several Kruja and Krasta tectonic windows and the Tithonian-Valanginian marly flysch sequence overlying huge ultrabasic bodies around the Mali i Bardhë tectonic window. The Mali i Bardhë window of Kruja zone, the Velivar-Kerçine window of Krasta zone including in it the Peshkopia, Kërçishti and Dibra e

Madhe windows of Kruja zone and the Okshtuni window, are observed within Korabi zone. The Tithonian-Valanginian marly flysch sequence transgressively covers the huge ultrabasic bodies around the Mali i Bardhë tectonic window of Kruja zone (Aliaj and Bushati 2019, Figure 4 and 5 and 7).

The two settings of ultrabasic bodies could be met in the Korabi zone: i) the ultrabasic bodies along the normal faults cutting the depositional sequences of Korabi zone, and ii) the imbricated ultrabasic bodies, which are transgressively covered by the Tithonian-Valanginian marly flysch sequence and located beneath the Korabi unit and around three sides of Mali i Bardhë tectonic window of Kruja unit as follows: in the Kalle, Vlesh, Dipjaka and Vrenjt on the west, in Biçaja pass (Varri i Sejmenit) and Bjeshka e Shehut stream on the east and in Radomira area on the north. The surrounding of Mali i Bardhë tectonic window is the only area that proves the presence of huge ophiolite bodies showing the roots of Mirdita ophiolites under the Korabi nappes. Both setting of the ultrabasic bodies identifies the existence of ophiolite massifs underlying the Korabi Zone.

The tectonic windows of Kruja and Krasta units observed within the Korabi zone have been formed due to the Late Miocene to present extensional tectonism, accompanied by normal faulting and evaporite diapirism. The created dome pattern horsts favored the erosion of the Mirdita and Korabi upper nappe sheets seen only at the margins of the Mali i Bardhë tectonic window of Kruja zone and the Okshtuni and Velivar-Kerçine tectonic windows of Krasta zone. The geological building of Korabi tectono-stratigraphic unit, including into its core several tectonic windows of both Krasta and Kruja unit, shows from top to bottom the following stack of nappe sheets: Korabi nappe, Mirdita ophiolite nappe transgressively overlain by the Upper Jurassic-Lower Cretaceous marly flysch sequence, and Krasta nappe overlying the Kruja "autochthon" (Aliaj and Bushati 2019, Figure 4 and 5).

The geological structure of the ophiolites in Albania with low angel dipping towards the northeast pass through a flexural ramp to the flat bottom under the internal molasse basins. Belostockij (1978) said that the ultrabasic massifs are in the shape of flat constantly synform bodies, underlying by the sialic crust rocks.

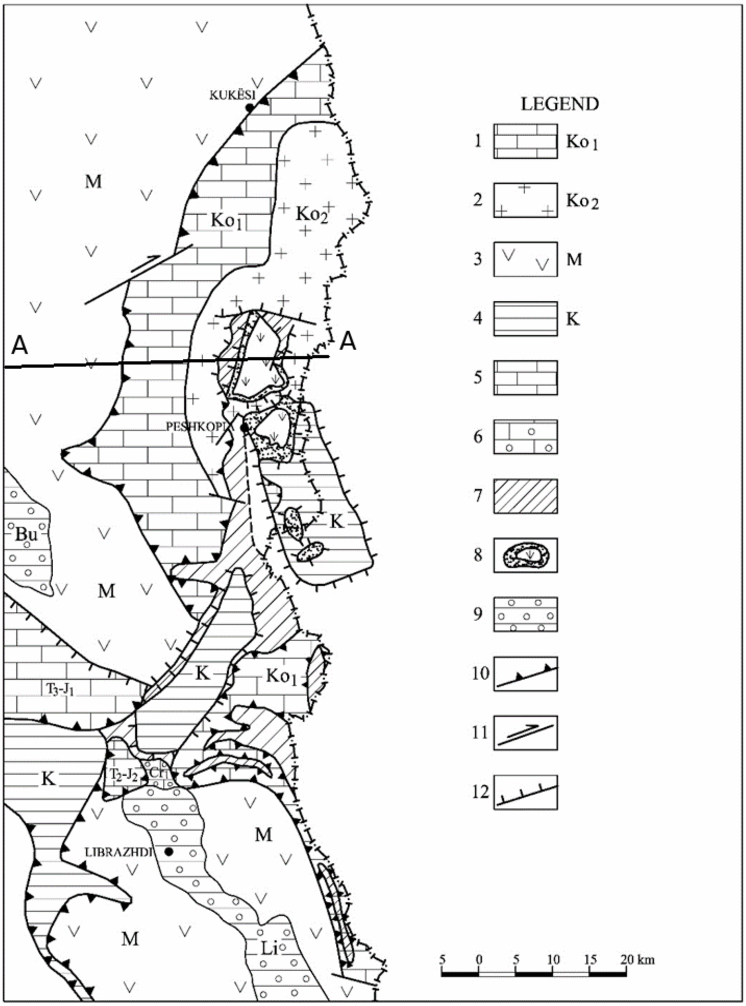

Fig. 4: Tectonic Map of Kukes-Librazhd area (Aliaj and Bushati 2019). Korabi Zone: 1- Triassic-Jurassic carbonate sequence and 2- Ordovician-Silurian schist sequence. 3-Mirdita Zone: ophiolites and their sedimentary cover, 4- Krasta Zone, 5- Triassic-Jurassic limestones, 6- Lower Cretaceous Gosaw, 7- Upper Jurassic-Lower Cretaceous marly flysch underlying Korabi nappes, 8- Kruja Zone evaporite dome surrounded by the Upper Eocene-Lower Oligocene flysch, 9- Molasse basins: Li- Librazhdi, Bu- Burreli, 10- Overthrust, 11- Strike-slip dextral, 12- Normal fault. (see also Figure 7)

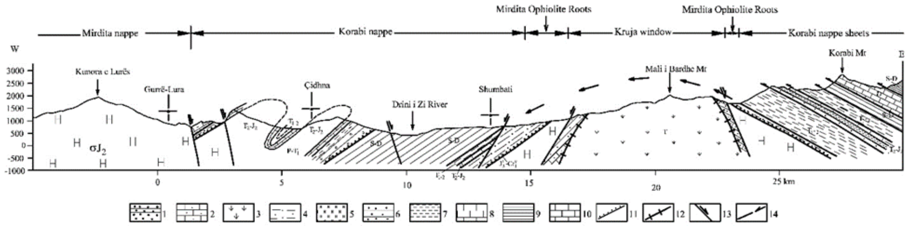

Fig. 5: Kunora e Lurës-Korabi Mt. Geological Section (profile A-A in Figure 4, from Aliaj and Bushati 2019). Kruja Zone: 1- Upper Eocene-Lower Oligocene flysch, 2- Late Cretaceous neritic limestones, 3- Triassic evaporites. Mirdita Zone roots: 4- Upper Jurassic-Lower Cretaceous marly flysch underlying Korabi nappes, 5- Middle Jurassic huge ultrabasic bodies. Korabi Zone: 6- Permian-Lower Triassic Verrucano, 7- Lower-Middle Triassic terrigenous deposits, 8- Middle Triassic-Middle Jurassic limestones, 9- Silurian-Devonian schists, 10- Devonian limestones. 11- Transgressive setting, 12- Tectonic contact, 13- Normal fault, 14- E-W displacement of Korabi nappes.

The most complete ultramafic sequences form large relatively intact thrust sheets (termed ‘ophiolite massifs’). An undisturbed local transition exists between the Western and Eastern-type ophiolites. However, a number of lines of evidence demonstrate that the Western and Eastern-type ophiolites were synchronously formed and emplaced as a single thrust sheet (Robertson and Shallo 2000).

The Mirdita ophiolites in the shape of a very large synclinal structure with flanks of low-dipping angles and the flat floor and with ultrabasic rocks at their bottom overlie Triassic-Jurassic carbonates (Xhomo *et al*., 2005). Kodra and Hoxha (2019) pointed out that the Mirdita ophiolites present a “megasynclinorium” structure consisted of two “synclinorium” overlapping each other: a) the “synclinorium” of continental formations both on the periphery and the floor of the ophiolites and, b) the “synclinorium” of the ophiolites with Jurassic ophiolites in the center and Triassic ones on the periphery and their floor.

The Cenozoic tectonic evolution of Eastern Albania consists of two periods of extensional deformations, the first in Middle Eocene-Late Miocene (Pannonian) and the second in Latest Miocene (Pontian)-Quaternary, separated by a short compressive phase at the end of Late Miocene (end of Pannonian/Tortonian). In the Latest Miocene (Pontian) time began forming the system of the Ohrid, Prespa and Devolli lake basins along the Drini normal fault zone N-S striking or parallel to it. The commencement of Neotectonic period in Late Miocene-Pliocene was distinguished by extensional tectonics, which affected the interior of the country and created their horst-graben structure (Pashko and Aliaj 2020).

The Albanides lies on the south-westernmost part of the Eurasian plate, and is a convergent zone due to northeastward movement of the Adriatic plate (=Adria microplate). It is divided into two domains of present-day tectonic regime: a coastal domain of compression dominated by northwest to north-northwest striking thrusts and folds, and an interior domain of extension dominated by north striking normal faults (Aliaj *et al.*, 2004).

The Kruja Zone is before considered to take part within the external domain in compression (Aliaj 2006). The aftershocks map of 2019 Durres Mw 6.4 earthquake shows that only the area west of Dajti Mt. thrust (part of Kruja Zone) is situated in the external domain in compression.

The Kruja Zone towards south of Elbasan-Diber transverse is divided into two subzones with typical evolution and structural features: a) Tomorri subzone, including Tomorri, Kulmaka and Qeshibeshi brachyanticlines, with features of an internal carbonate platform up to Lower Cretaceous (Albian), and an external platform with subsiding tendency towards the Ionian basin from Late Albian to Eocene, and b) Dajti subzone which includes Valesh and Tervolli crest anticlines with features of an internal carbonate platf west-east trending orm from Cretaceous up to Eocene. The Kruja Zone during the neotectonic period of development was affected by extensional tectonics that caused its fracturation via longitudinal and transversal normal faulting. Tomorri anticline towards the north abruptly plunged due to the cutting by east trending normal faults (Sadushi *et al.*, 2015). Kulmaka structure is fractured by three longitudinal and some transversal normal faults (Shteto *et al.*, 1982).

The Kulmaka eastern flank is displaced by a normal fault northwest-southeast striking, forming its horst structure (Sadushi et al 2015). The Qeshibeshi brachyanticline presents another horst structure. Normal faults in Leskoviku and Postenan structures are also observed.

It is interesting to underline that east of Tomorr-Kulmaka structures, the Ostrovica Mt nappe of Krasta Zone is fractured by many transversal normal faults generally east trending, cutting also the underlying Oligocene Flysch of Kruja Zone (Shehu *et al.*, 1983, Aliaj *et al.*, 2020). SW-NE normal fault system is well developed in the Vikos National Park of Greece, just there where Vjosa river passes the Albania-Greece border (Carcaillet *et al.*, 2009).

The Dajt-Kruja mountain line of Kruja Zone is fractured by normal faults east-northeast striking which cuts also the molasse’s deposits of Tirana depression (Zuber 1943). The Tujani canyon of Tirana river presents an east-northeast normal fault that vertically displaced for about 400 m the Priska e Vogel Mt. (1239 m height) in the north from the Dajti Mt. (1613 m height) in the south.

Normal faults encounter also to the south of Dajti Mt. as in Letan Mt. and to the south of Elbasan, at the Shirgjani syncline located between the Sulova anticline to the west and Tervolli one in the east. The Elbasani transverse Quaternary graben structure shows a northeast normal fault system, that has been created due to the north-south extension.

The terrains of the Kruja and Krasta zones to the north of Elbasani up to the Mali me Gropa Mt. area are ruptured by a system of northeast trending normal faults (Xhomo *et al*., 2005). Such a system of normal faulting dislocating also terrains of Mirdita Zone is shown in the Geological Map of Albania, scale 1:200.000 (Biçoku *et al*., 1967).

Albania's most important thermal springs are situated in Kruja Province, including Uji Bardhe near Mamurras, Llixha and Hidraj near Elbasan, and Holta (Gramsh), Benje (Permet) and Sarandoporo (Leskovik). Most springs emerge in the periphery of carbonate structures as Uji Bardhe, but Llixha and Hidraj springs rise along the supposed tectonic faults developed in the Oligocene flysch (Eftimi and Frasheri 2016). Thermal water sources are located along normal faults in Kruja Zone, especially along SW-NE extending ones.

Velaj (2000; 2012) underlined that the Kruja zone is overthrust westwards on South Adriatic Basin along an evaporite level. The Kruja nappe is also testified by the outcroppings of the Kruja and Krasta units at the core of Korabi zone (Aliaj and Meço 1994; Aliaj and Bushati 2019). The underlying of the Kruja nappe at the bottom of the nappe stack is also underlined by (Xhomo and Kodra 2002).

The inferred geological data show that the Kruja tectono-stratigraphic unit affected by the normal faulting from Late Miocene to Recent represents the basal thrust of nappe stack that crops out.

The seismological, gravimetric and the magnetometric studies about the Earth crust structure of Albania show that its thickness increases from 9 km in Adriatic coast to 13 km in northwest of Albania (Xhomo *et al*., 2002).

The first seismological study about the Earth Crust Structure based on the first onset of P waves in seismological stations was carried out by Koçiaj (1989). The Earth crust thickness and Moho depth data for Albania are in the Table 1 reported.

Table 1 Earth crust structure data for Albania

Locations	***Crustal Thickness***	***Moho Depth***
Periadriatic Basin	From 12 to 24 km	40 km
Ionian Zone	From 15 to 34 km	36 km
Northeasten Albania	From 13 to 27 km	47 km
Southeastern Albania	From 17 to 30 km	43 km

Papazachos *et al*., (2004) used the P and S arrival times from regional earthquakes of the study area to determine the deep velocity structure of the Southern Adriatic-Eurasia Collision that is obtained by Robust Non-Linear Inversion of Travel Times. Their results show that the crustal thickness reaches up to 50 km under inner Albanides, similar to what is found in other studies, further south along the Hellenides mountain chains, whereas in the South Adriatic Sea a thin crust of 25-30 km is evidenced. The crustal thickening is rather asymmetric, as the crust is also thinning rather abruptly towards the Balkan area (Kosovo-FYROM region), although thinning is at edge of the studied area. In the shallow layer low velocities are found along the coastal part of Albania (pre-Adriatic depression) indicating the presence of thick low velocity sediments, taking their maximum in the southernmost part of Albania coast. The thick sedimentation is observed along the coastal Albania, around 10 km where low velocities (Vp ~ 5.3 km/s, Vs ~ 3.1 km/s) are found. A mid-crustal low velocity layer between the depth of 5-7 km and 14-17 km is found in various places of thick crust area.

Frasheri *et al*., (2009) underlined that the Moho discontinuity plunges from 25 km in central part of the Adriatic Sea to 43-52 km at the Eastern Albanides. The geological-geophysical Albanides-1 profile passing from Falco-1 borehole through Adriatic Sea and in Albania through Seman-Kuçova up to Bilishti shows that the Moho discontinuity deepens from 30 km in Falco-1 to 40 km in the east of Mirdita Zone with the maximal depth of around 45 km below the Krasta Zone.

Based on the seismic sounding profile between the Petrovac (Montenegro) and Raška (Serbia) results that the Moho boundary plunges from 30 km in the Adriatic Sea to 35 km in Petrovac and up to 45 km in Raška (Glavatovic 2000).

Veizaj (1995) investigated the relationships between Albanides orogeny and Apulian platform based on the gravity data. The Moho-depth Map for Albania illustrates that Moho depth ranges from 24 km in Adriatic and Ionian seas to under 40 km in the Eastern Albanides, reaching more than 46 km in the "Alps-Korab-Erseke" areas. The gravity modeling results show that the Moho boundary deeps in both sides, from 25 to 46 km under Alps and Korabi zones of Albanides, and from 25 to 38-40 km under Kalabrian zone of Apennines. Nearly the same configuration has the crustal basement, which deeps gradually from 12-13 km near Gargano and Salentina peninsula to 16, 18, 20 km and more towards the Albanides.

Geological framework of the Albanides-Adria microplate collision

In Albania and Greece, along the southern convergent margin of Eurasia Plate, a northern segment of the margin belonging to the Adriatic continental collision, and a southern one belonging to the Aegean (Hellenic) Arc related to active oceanic subduction could be distinguished. The Adriatic-Eurasian collision is taken up along the western coast of former Yugoslavia, Albania and central Greece. The boundary between the Aegean Arc and the Adriatic collision is the Cephalonia Transform Fault (Figure 6).

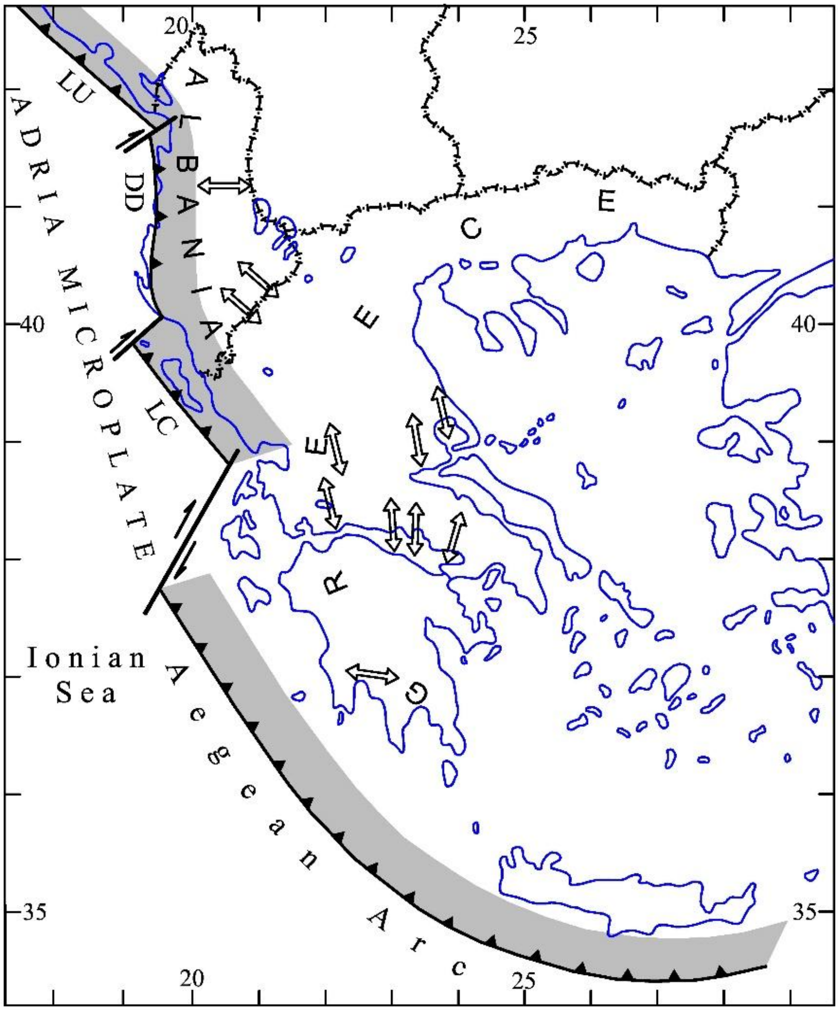

Fig. 6: Southern convergent margin of Eurasia Plate: Adriatic collision and Aegean Arc (modified by Aliaj 2006 with separation of two segments in the Albanides collision zone). Segments of Albanides collision zone are noted by capital letters: LC- Lefkas-Corfu, and DD-Dhermi-Durres. LU- Lezha-Ulqini segment belongs to the Dinarides.

In Albania, the Adria Microplate collides with the Albanides (frontal part of the Eurasian Plate). The Adria is a continental microplate, underlying eastern Italy and the Po plan, and the Adriatic Sea, west of the Dinarides that behaved as a tectonic indenter during the convergence between Africa and Europe.

The Albanides is divided into two active tectonic domains: an external domain in compression characterized by the reverse faulting, and an internal domain in extension characterized by the normal faulting.

The convergent boundary between the Albanides and Adria Microplate, based on the oil and gas seismic exploration carried out by foreign companies, is now well constrained to be located along the Adriatic and Ionian coasts (Aliaj *et al*., 1996, Aliaj 2006). From Dhermi-Othoni Island strike-slip to Vlora city it follows the contact between Sazani and Ionian tectonic units and then from Panaja through Frakulla to Durresi anticlinal line of quasi-northern extension it is deeply buried under Middle Miocene-Pliocene molasses of the Periadriatic Foredeep Basin (see Figure 7).

The inferred geological data show that the frontal thrust of Albanides which is cut and displaced by the northeast-southwest extending Dhermi-Othoni Island and Lezha-Drini Bay dextral strike-slip faults, is divided into two following segments: the north-west trending Lefkas-Corfu segment, and the generally north-south trending Dhermi-Durres one which are built by the Ionian Zone. The west-northwest trending Lezha-Ulqini segment locating into the Dinarides is built by the Kruja (=Dalmatian) Zone (see figures 6 and 7). A passage of the orogenic front from the Ionian Zone in the Adriatic offshore, south of the Drini Bay-Lezha dextral strike-slip fault, to the Kruja (=Dalmatian) Zone north of it, is assumed.

The displacements occur along the Ionian thrust front at Albanides and along the Kruja-Dalmatian thrust front at Dinarides (Figure 7).

The Lefkas-Corfu segment where the orogenic front, north-west extending, built by the Ionian Zone, overthrusts the Apulian platform (Sorel 1989). Further on, the orogenic front accords with the Dhermi -Othoni Island dextral strike-slip fault, north-east extending, along the morphological accident in the transition from the continental shelf to the Ionian offshore bathyal depths. Here a thin imbricated section of Ionian Zone was largely displaced south-west for about 45 km thrusting the Apulian platform.

The Dhermi-Durres segment encounters underneath the Mali i Kanalit Mt. backthrust and it follows northwards along the western flanc of the Lungara Mt. anticline up to Vlora city. Then from the Panaja anticline the front of the orogen, buried under molasses of Middle Miocene on the onshore coastal terrains of the Periadriatic foredeep, follows the Frakulla-Durresi anticlinal line of quasi-northern extension, as well as in the Adriatic offshore as far as the Drini Bay-Lezha dextral strike-slip fault.

The Dhermi-Durres segment of Albanides frontal thrust is situated between the Lezha-Drini Bay and Vlore-Elbasan transfer faults. The Vlore-Elbasan transversal zone is marked, from southwest to northeast, by the Lushnja flexure, the Dumre diapir, the Elbasani Quaternary depression, the Labinoti transversal structure and the Golloborda transversal horst of Krasta Zone; further it follows in fragmentary parts in the Tetova Quaternary basin of North Macedonia and ends at Morava e Binçes Quaternary basin in Kosova (Aliaj 1988; Aliaj and Pojani 2003; Aliaj 2012).

The Elbasan-Vlora Transfer Zone dextrally offsets the Kruja and Ionian Nappes. It is marked by dextrally dragged folds and thrusts, in addition to the thrusts that steepen and offset all Neogene basal unconformities (Handy *et al*., 2019). Current tectonics along the Vlore-Elbasan-Diber transversal structure N-E trending is expressed by an earthquake belt of M>6. It is considered the most potential transversal seismogenic zone in Albania (Sulstarova *et al*., 2000).

The active Albanides collision thrust dislocated by transfer faults and the active reverse faults of Ionian Zone are shown in blue color. LD- Lezha-Drini Bay and DO- Dhermi - Othoni Island dextral strike slip faults separate DD-Dhermi-Durres and LC- Lefkas-Corfu segments of Albanides collision thrust. The LU-Lezha-Ulqini segment belongs to the Dinarides collision thrust. The displacements occur along the Ionian thrust front at Albanides and along the Kruja-Dalmatian thrust front at Dinarides.

1-1 Durresi hill-Korabi Mt., 2-2 Ardenica hill - Dumre diapir - Skenderbeu village - North Macedonia border and 3-3 Mali i Kanalit Mt - Mali i Thate Mt geological cross sections show the fault geometry of the Main Albanides Thrust (MAT) that separates the Adria microplate underthrusting beneath the Albanides (Figure 13- 15).

The Vlore-Elbasan-Diber transversal zone formed due to different direction of the Adria microplate compressional axes: towards northeast along the Lefkas-Corfu segment and towards the east along the Dhermi-Durres segment. It represents a dextral transfer zone characterized by plicate and disjunctive deformations that affect the tectono-stratigraphic units and molasses basins structures. The Dhermi-Othoni Island strike-slip fault can be considered as the southwestern segment of the Vlore-Elbasan-Diber long transversal zone.

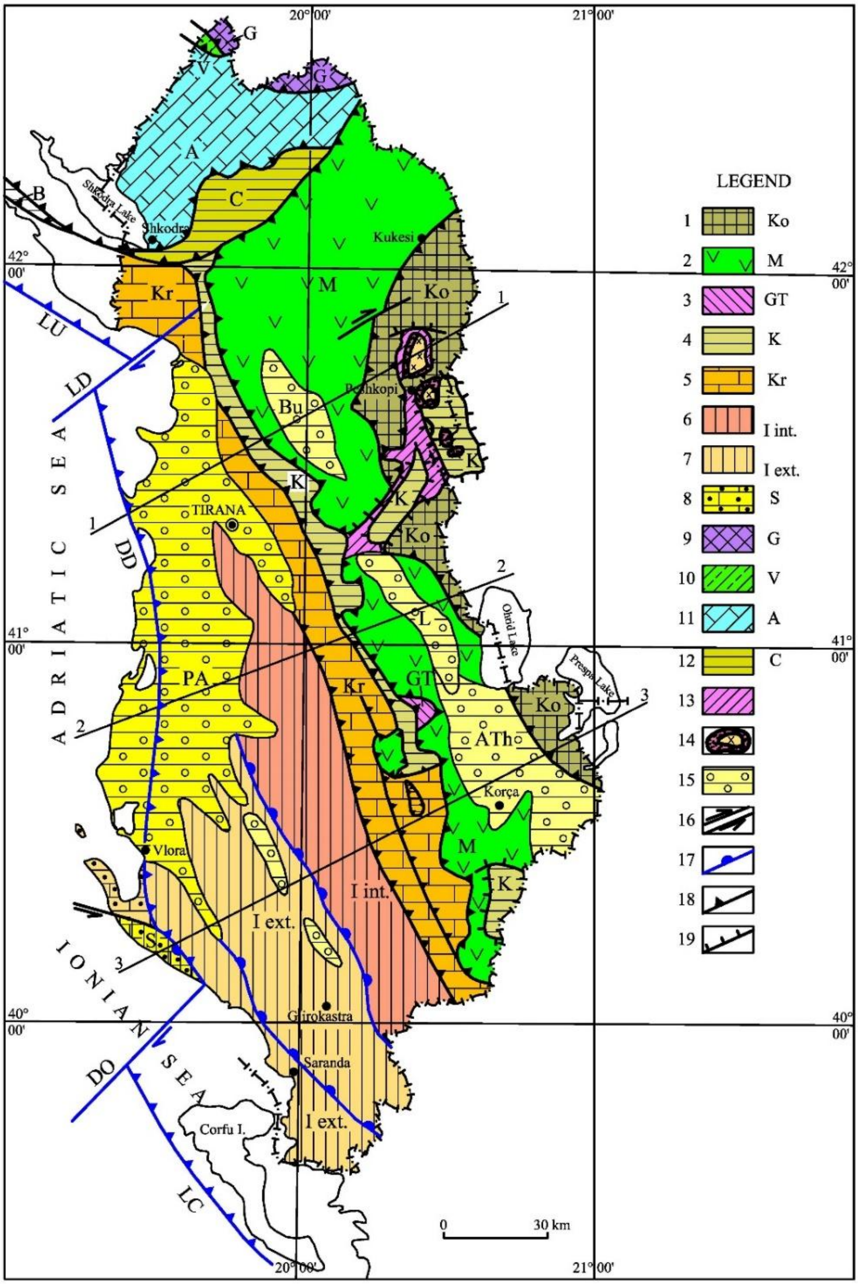

Fig.7: Tectonic Map of Albania.

GPS velocities in the external Albanides, from north to south, show changes in direction and norms. GPS results demonstrate a southwestward motion of points located in external Albanides relative to Apulia with important north to south increase of their velocities, which arrive the maximum velocity of greater than 5 mm/year south of the dextral Othoni Island-Dhermi transfer fault (Jouanne *et al*., 2012). The present-day greatest velocity evidenced to the south of Othoni Island-Dhermi dextral strike slip fault well accords with south-west large displacement for about 45 km of the Ionian Zone frontal thrust (Aliaj 2012).

The useful data for the depth of top carbonates of Adria platform we found in geological cross sections of Geological Map of Albania, scale 1:200.000 (Xhomo *et al*., 2005). The top carbonate depths in the Adriatic plate are the followings: 12-14 km at Ardenica and Durresi hills, 3 km west of Sazani Island and about 4 km west of Mali Kanalit Mt.

A mid-crustal low velocity layer with the depth varying between 5-7 km and 14-17 km is found along the coastal part of Albania (pre-Adriatic depression) (Papazachos *et al*., 2004). The low velocity layer can be suggested to be the location of earthquake sources. A Pc phase registered from the April 15, 1979 earthquake showed a low velocity layer at the depth of 20-25 km where it occurred (Aliaj and Muço 1980).

The seismic and geological cross sections passing through the Durresi hill (Adriatic offshore north of Durres), Ardenica hill (north of Fieri) and Llogora pass (25 km south of Vlora) show a significant face to face (tête à tête) collision between the Albanides and Adria Microplate.

The Apulian Cretaceous carbonates of Mali i Kanalit Mt (Sazani unit) backthrust to the Upper Triassic dolomites of Çika Mt. (Ionian Zone) indicates the tête à tete collision of the Sazani Zone (a part of the Apulian platform) with the Ionian Zone at Llogora pass, south of Vlora (Figure 8).

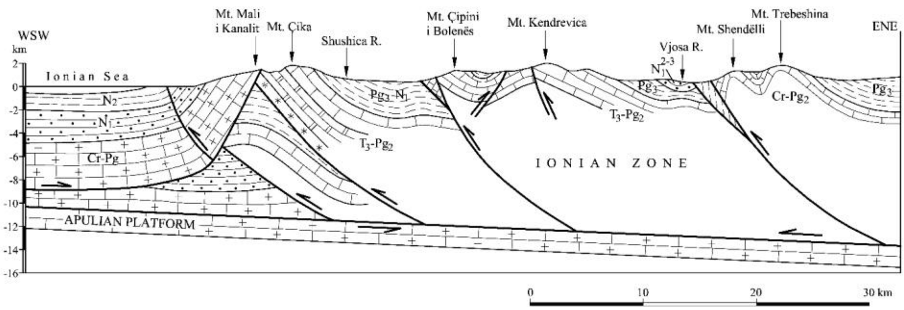

Fig. 8: Geological cross section from Ionian offshore, 25 km south of Vlora city, shows a face-to-face collision between the Sazani Zone and the Ionian Zone thrust-bounded imbricates that form a triangular zone resting on the Apulian platform decollement surface.

The seismic and geological cross sections passing through the Ardenica and Durresi hills show that thick Oligocene to Quaternary clastic sediments of the South Adriatic Basin (=Albanian Basin) were detached from their carbonate substratum through a detachment fault maybe at the base of Oligocene clastics. The clastic sediments were largely backthrusted onto the Ionian Zone frontal structures, which are deeply buried underneath the Middle Miocene-Pliocene molasses of Periadriatic Foredeep Basin (Figure 9 -12).

The Periadriatic Foredeep Basin consists of Middle-Upper Miocene and Pliocene molasses. The structure of Pariadriatic basin consists of several Mio-Pliocene linear and narrow anticlines and wide synclines that have an NNW-SSE extension. The Mio-Pliocene anticlines are superimposed on thrust or backthrust faults that are named as overfault anticlines (Aliaj 1971; 1988), or as folds 'placed in narrow zones of some big faults found under the Neogene cover' (Biçoku 1964).

An excellent seismic section passing through the Ardenica hill (north of Fieri) reveals the gently east dipping Cretaceous-Eocene carbonate substratum of South Adriatic Basin (Adria Microplate) beneath the buried Ionian structures overlain by the Middle Miocene-Pliocene molasses of Periadriatic basin. Here the eastwards backthrust of the clastic sediments of the Albanian Basin for about 50 km onto the Patos-Verbasi carbonate structures is identified (Figure 9).

To the west of Patos-Verbasi carbonatic anticline, the Ardenica-18 well of 6700 m depth has explored the Middle-Upper Oligocene flysch of Ionian Zone indicating the presence of another carbonatic anticline structure. The seismic section shows that these carbonatic structures are 'thrust-bounded imbricates', known as a duplex structure. Here the two thrust-bounded imbricates of Ionian Zone are located on the Albanian Basin top placed at 12-14 m depth (Figure 10).

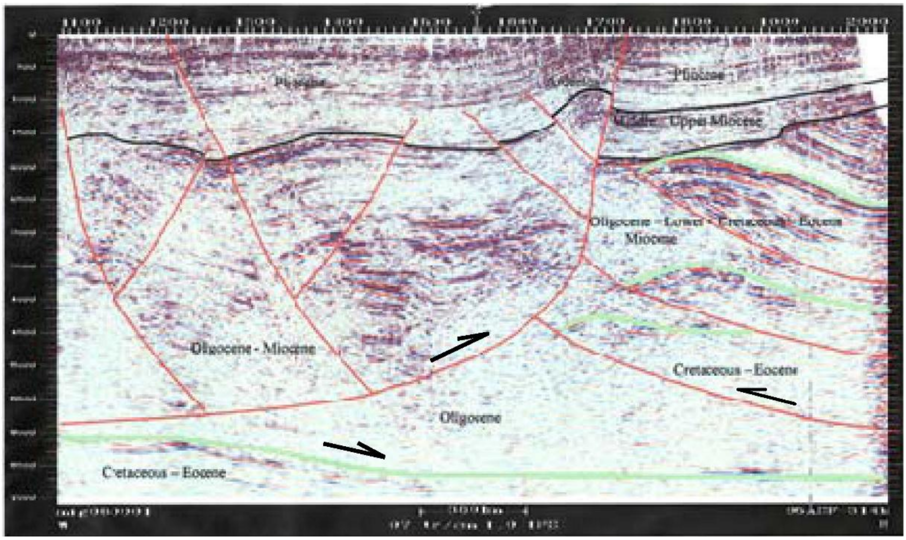

Fig. 9: Seismic section from Adriatic coastline eastwards, passing slightly north of Fieri town, shows the large backthrust of deformed clastic sediments of Albanian Basin over the Ionian Zone blind thrust-bounded imbricates. Beneath them is evidenced the gently east dipping Cretaceous-Eocene carbonate substratum of South Adriatic Basin (From Aliaj 2006).

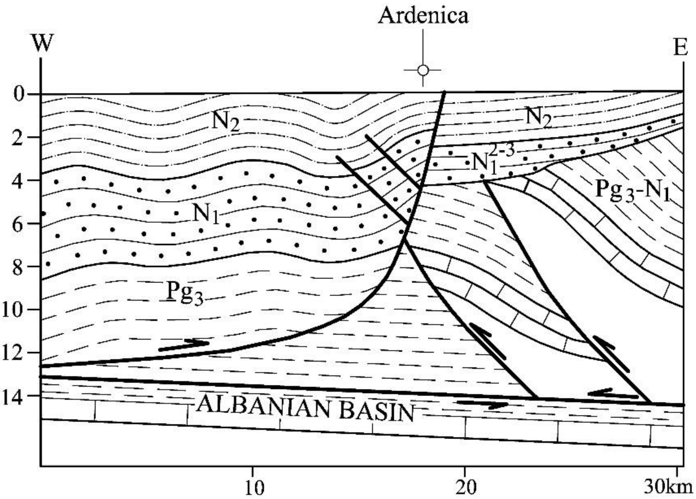

Fig. 10: Geological cross section through the Ardenica hill (north of Fieri town) shows the face-to-face collision between the backthrust of Albanian Basin clastic sediments and the Ionian Zone blind thrust-bounded imbricates unconformably overlain by the Middle Miocene-Pliocene molasses of Periadriatic Foredeep Basin. It locates on main basal thrust of Albanides.

The Durresi hill Upper Miocene molasse backthrust collides with the Pliocene molasses at the south and north of Porto-Romano. At the northwestern part of the Durresi anticline, the Tortonian sediments with west dipping angle 60-70^o collides with the Pliocene sediments east dipping 60^o (Papa *et al*., 1991). At the hill relief to the south of Porto-Palermo, the Upper Miocene sediments west steep dipping (80-85^o) that take part in the Durresi backthrust, collides with northeast dipping (60-70^o) Pliocene sediments.

Seismic section through Adriatic offshore, 15 km north of Durres city, shows that the clastic sediments of the Albanian Basin were largely backthrusted onto the frontal margin of buried Ionian zone forming a triangular zone at the depth, the same as at the Ardenica hill (Figure 11). Here, the backthrust of Oligocene to Quaternary clastic sediments has cut and displaced the marine Quaternary sediments. It identifies here the present-day activity of the Adria-Albanides collision.

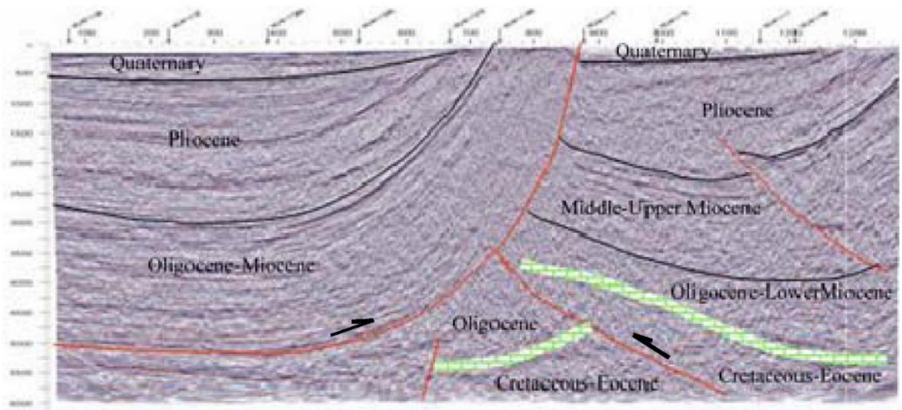

Fig. 11: Seismic section through Adriatic offshore, 15 km north of Durresi town, shows the backthrusting of clastic sediments of Albanian Basin cutting the Quaternary sediments of the Periadriatic Basin that forms a triangular zone with the Ionian Zone blind thrust-bounded imbricates (From Aliaj 2006).

The strong November 26, 2019 Mw 6.4 Durres earthquake generated by the Adria Microplate-Albanides collision thrust shows the activation of the NNW-SSE striking Durresi frontal fault, well seen on seismic section, and the Shkoza fault, both dislocating the Durresi and Shkoza Mio-Pliocene anticlines (Figure 11 and 12).

Two molasse basins bounded by the Preza backthrust could be distinguished in the Tirana-Durresi area of Periadriatic basin: the deepest Durresi molasse basin in the west, and Tirana molasse basin in the east. The Preza backthrust acted as a synsedimentary normal fault during the Mio-

Pliocene molasse sedimentation. It became a backthrust fault at the end of Pliocene due to the compressional stresses towards the east by Adria microplate. Both the blind thrust-bounded imbricates could be found at the collision frontal part of the Ionian Zone, deeply buried under Durresi basin (Figure 12).

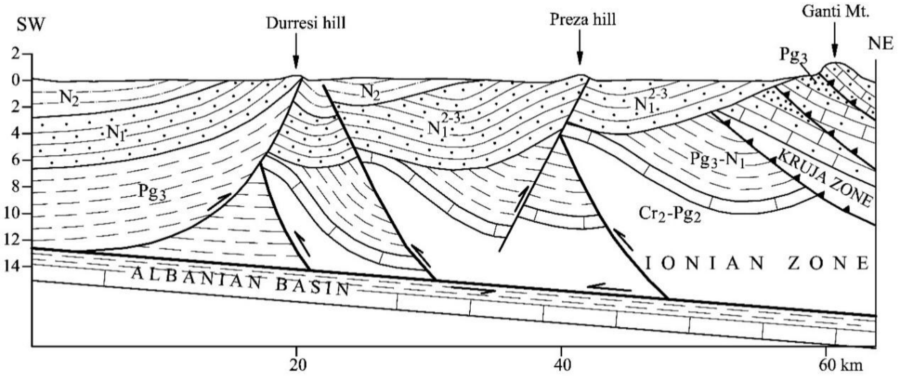

Fig.12: Geological cross section through the Durresi hill-Preza hill-Ganti Mt. shows the face-to-face collision between the Albanian Basin backthrust and the Ionian Zone blind thrust-bounded imbricates unconformably overlain by Middle Miocene-Pliocene molasse of Periadriatic basin. It locates on the main basal thrust of the Albanides.

Fault geometry of underthrusting Adria microplate beneath the Albanides fold and thrust belt

The fault plane solutions for the November 26, 2019 Mw 6.4 Durres earthquake and other earthquakes that occurred in Albanides collision zone and the inferred geological background of the Albanides and separately of the Periadriatic Foredeep basin are used to investigate the fault geometry of the Adria Microplate underthrusting beneath the Albanides. The relative slip-on fault planes, deduced from studies of focal mechanism solutions, plays an important role in deciphering tectonic plate movements (Boore *et al*., 1981).

Mattawer (1983) and Ni and Barazangi (1984) based on the geological-geophysical and seismotectonic studies in the Himalayas concluded that the subduction occurs also in continental crust.

Mattawer (1983) under the example of the Himalayan Mountains Collision, the highest in the world, formulated the subduction-collision, mechanism which simultaneously induced folding and thrusting, as well as the nappe emplacement of tectono-stratigraphic units one over the other. He pointed out that the subduction preceding the collision can occur both in oceanic and continental crust.

Ni and Barazangi (1984) investigating the seismotectonics of the Himalayan Collision Zone show that the Indian continental Plate underneath the Himalaya is not much different from that observed along the oceanic subduction zones. The locations and focal mechanism solutions of moderate earthquakes at 10-20 km depth indicate shallow (≤ 30^{o}) north dipping thrust, which defines a part of detachment that separates the underthrusting Indian Plate from the Lesser Himalayan crustal block. They suggested that great Himalayan earthquakes (M> 8) occur along the same detachment surface as defined by thrust-type.

Many seismotectonic studies about the Himalayan Collision Zone, especially those concerning the geometry of the underthrusting Indian Plate beneath the Himalaya (Ni and Barazangi 1984; Duputel *et al*., 2016; Elliot *et al*., 2016; Arara *et al*., 2017; Mendoza *et al*., 2019) were helpful to the present investigation, in addition to Ganas *et al*., (2020a and b) addressing the M 6.4 Durres earthquake 2019, and the earthquake in Zakynthos, Greece in 2015 and Handy *et al*., (2020) addressing the M6.4 Albanian earthquake of 2019.

The external zones of the Albanides are formed through the subduction-collision mechanism. They represent the large deformed units of sedimentary crust, detached from the subducted parts of the former Adriatic plate and overthrusted one over the other towards southwest (Aliaj 2000).

The published fault plane solutions for the November 26, 2019 Mw 6.4 Durres earthquake and other earthquakes that occurred in Albanides Collision Zone, reported in the table 1-3, are used to investigate the geometry of underthrusting Adria Microplate below the Albanides.

EMSC published many quick focal mechanism solutions for both Durres earthquakes: September 21, 2019 Mw 5.6 and November 26, 2019 Mw 6.4 Durres earthquake determined by different institutions (USGS, INGV, GFZ, IPGP, CPPT).

Table 1: Focal mechanism solutions for the November 26, 2019 Durres earthquake determined by various agencies.

Institute	Mw	Depth (km)	Strike (^{0})	Dip (^{0})	Rake (^{0})	Strike (^{0})	Dip (^{0})	Rake (^{0})	Source
GFZ	6.4	26	151	72	89	335	18	98	1
GCMT	6.4	24.1	145	68	79	351	25	114	2
USGS	6.4	19.5	156	63	89	338	27	92	3
CPPT	6.4	15	168	69	104	312	25	57	4
INGV	6.2	21	134	82	84	350	10	126	5

Sources:1. Gfz Potsdam, German, 2. Global cmt.org, 3. Usgs.gov, 4. CSEM, 5. Ingv.Italy.

The fault plane solutions determined by various agencies identify that the November 26, 2019 Mw 6.4 Durres earthquake was generated by an NNW-SSE striking (337^{o}) blind thrust fault low-angle (21^{o}) dipping towards the east (97^{o}) that locates within the frontal area of the main basal thrust of the Albanides.

Table 2. Fault plane solutions of the events of magnitude greater than 5 of the November 26, 2019 Durres earthquake determined by GFZ

Events	Mw	Strike (^{0})	Dip (^{0})	Rake (^{0})	Strike (^{0})	Dip (^{0})	Rake (^{0})
November 26, 2019 2:54	6.4	151	72	89	335	18	98
November 26, 2019 6:08	5.5	139	65	85	332	22	102
November 27, 201914:45	5.3	155	63	89	337	27	91

The focal plane solutions for the main shock and the two aftershocks of magnitude greater than 5 of the November 26, 20919 earthquake determined by GFZ show that they occurred on the NNW-SSE striking (335^{o}) frontal blind thrust of low-angle (22^{o}) dipping towards the east (97^{o}) locating on the main basal thrust separating the Adria microplate underthrusting beneath the Albanides.

Glavatovic (2000) said that the strongest April 15, 1979 Mw=6.9 Montenegro earthquake occurred about 100 km northwards of Durres and on low-angle (14^{o}) thrust fault dipping towards northeast (35^{o}).

The November 26, 2019 Mw 6.4 Durres earthquake ruptured two blind imbricate thrust-bounded faults that locate on the main basal thrust of the Albanides. Therefore, it ruptured the Main Albanides Thrust highlighting its ramp and flat geometry.

The November 26, 2019 Mw 6.4 event was preceded by an Mw 5.6 event that occurred on September 21, 2019 with the same type of faulting kinematics. The geometry and kinematics of both events are similar (see EMSC published focal mechanisms for both 2019 Durres earthquakes).

The fault plane solutions for the earthquakes with M > 5 occurred in Albanides collision Zone show that they ruptured thrust faults of low-angle dipping, and reverse faults of high-angle dipping (Table 3).

Table 3. Focal mechanism solutions for 12 earthquakes with M > 5 that occurred in Albanides Collision Zone

No	D M Y	F^0 L^0 H	Mw	Plane 1 Str. Dip	Plane 2 Str. Dip	P Az. Dip	T Az. Dip	R/Fault Plane Types
1	18 03 1962	40.70 19.60 27	6.2	355 12	155 78	245 33	65 57	4 –T
2	16 08 1966	40.16 19.75 20	5.2	166 54	26 44	274 5	18 68	6-R
3	03 04 1969	40.70 20.00 21	5.8	336 50	164 40	69 05	219 84	1-R
4	19 08 1970	41.10 19.80 21	5.4	332 19	152 71	69 5	208 83	1-T
5	16 09 1972	40.13 19.80 15	5.3	316 50	254 60	196 8	292 53	5-R
6	24 11 1972	39.39 20.43 9	5.4	243 46	125 65	188 11	83 53	5-R
7	22 11 1975	39.92 20.11 34	5.3	329 50	78 68	200 11	301 46	6-R
8	16 11 1982	40.88 19.59 17	5.4	323 27	141 63	232 18	49 72	2-T
9	21 11 1985	41.48 19.37 8	5.6	345 15	135 77	231 32	35 57	3-T
10	09 01 1988	41.20 19.74 30	5.7	323 25	166 67	249 21	93 67	3-T
11	16 06 1990	39.16 20.54 7	5.5	352 33	154 58	251 13	37 75	3-T
12	13 06 1993	39.28 20.49 9	5.3	325 30	127 61	224 16	16 72	3-T

R-References: 1. Anderson and Jackson (1987), 2. Baker et al. (1997), 3. Louvari et al. (1999), 4. Ritsema (1974), 5. Sulstarova (1986), 6. Muço (1994). Fault Plane Types: T- Thrust fault, R-Reverse fault.

Thrust faulting earthquakes, below analyzed, have occurred along the marginal part of the Albanides Collision Zone. The March 18, 1962 Mw=6.2 earthquake occurred near Fieri town on a very low-angle (12°) thrust fault dipping towards the east. The August 19, 1970 Mw=5.4 earthquake occurred northwest of Dumre diapir (Elbasani district) on a thrust fault low-angle (19°) dipping towards northeast. The November 16, 1982 Mw=5.4 earthquake occurred west of Lushnja town on a low-angle (27°) thrust fault dipping to northeast. The November 21, 1985 earthquake Mw=5.6 occurred west-southwest of Lezha town in Adriatic offshore on a low-angle (15°) thrust fault dipping towards northeast. The January 9, 1988 event occurred southwest of Tirana on a thrust fault low-angle (25°) dipping towards the northeast.

All the aforementioned earthquakes, located along the coastal part of Periadriatic Foredeep Basin from Fieri to north of Durresi, occurred on NNW-

SSE striking (336^o) thrust faults of low-angle (20^o) dipping towards the east-northeast.

The June 13, 1990 and June 13, 1993 earthquakes occurred in northern Greece coasts on low-angle (33^o and 30^o, respectively) dipping thrust faults.

Reverse faulting earthquakes have occurred on Çika, Kurveleshi and Berati anticlinal belts of Ionian Zone as below analyzed. The April 3, 1969 earthquake occurred north of Memaliaj town at the frontal thrust of Berati anticlinal belt on a reverse fault high-angle (56^o) dipping to northeast. The September 16, 1972 earthquake occurred at the frontal thrust of Kurveleshi anticlinal belt on a high-angle (50^o) reverse fault, northeast dipping. The November 24, 1972 earthquake occurred within Ionian Zone width (Northern Greece) on a reverse fault low-angle (65^o) dipping towards northeast. The November 22, 1975 earthquake occurred near to Delvina town in frontal part of Mali i Gjere anticline on a high-angle (50^o) reverse fault, northeast dipping.

General characteristics of reverse fault-plane solutions is that both plane are of high-angle dipping, showing that deep parts of the crust are in nowadays involved in the deformation by reverse faulting tectonics.

The published focal mechanisms for Durres 2019 and other earthquakes presented in tables 1-3 that occurred in the Albanides collision Zone fall into two categories: a) low-angle thrusting planes NNW-SSE striking, and b) high-angle reverse faulting planes generally NNW-SSE striking.

Thrusting faulting area is restricted to a narrow belt of 20-25 km wide that follows Adriatic Sea coast along the Dhermi-Durres thrust fault segment. The main azimuth of NNW-SSE striking planes is 336^o with low-angle 20^o dipping to the east-northeast.

Reverse faulting area is situated to the east of thrust faulting area, starting from the south of Dumre diapir with Berati anticlinal belt and southwards it enlarged with Kurveleshi and Çika anticlinal belts arriving the width of 60 km at south of Vlora (Llogora pass), and to the southeast of Dhermi-Othoni Island transfer fault along the Lefkas-Corfu segment it enlarged to 90 km width (Figure 7).

Focal mechanism solutions of the earthquakes occurring in the Albanides collision Zone show that movements on thrust and reverse faults causes the deformation of Earth crust attributed to the continental collision between the Adriatic block and Eurasia plate.

The fault plane solutions of Fieri earthquake (March 18, 1962 Mw 6.2) and of Lezha SW in Adriatic offshore earthquake (November 21, 1985 Mw 5.6) which occurred on the Albanides-Adria collision thrust show that they were generated by low-angle (12^o and 15^o respectively) dipping towards the east-northeast thrusts located on the main basal thrust of the Albanides.

The fault plane solutions of southwest Tirana earthquake (January 9, 1988 Mw 5.7) and of NW Dumre diapir earthquake (August 19, 1970 Mw 5.4) which occurred before the Kruja nappe front show that they were generated by low-angle (25^o and 19^o) dipping faults that could be located within the mid-crustal ramp.

The inferred data are taken into consideration to assess the low-angle dipping of the Main Albanides Thrust: 10-15^o for the flat co-seismic decollement portion and 20-25^o for the mid-crustal ramp.

Based on the earthquake fault plane solutions and the inferred geological background is investigated the fault geometry of the Adria microplate underthrusting beneath the Albanides that is named the Main Albanides Thrust (MAT).

The Durresi hill - Korabi Mt, and Ardenica hill - Dumre diapir - North Macedonia border geological cross sections crossing the South Adriatic Basin (Figure 13 and 14) and Mali i Kanalit Mt - Mali i Thate Mt geological cross section crossing the Apulian platform (Figure 15) show the fault geometry of MAT along the Dhermi-Durres segment of Albanides collision thrust front. To the south of Dhermi-Othoni Island strike-slip the Albanides collision thrust passes along the Lefkas - Corfu segment.

The November 26, 2019 Mw 6.4 Durres earthquake ruptured two blind imbricate thrust-bounded faults that locate on the main basal thrust of the Albanides, i. e. it ruptured the Main Albanides Thrust highlighting its ramp and flat geometry (Figure 13).

The investigated fault geometry of the Adria microplate underthrusting beneath the Albanides named the Main Albanides Thrust (MAT) consists of following segments: i) the tête à tête Adria block backthrust to Albanides frontal blind thrust fault, followed by ii) a flat (10-15^o) coseismic décollement surface northeast dipping, that ends on a iii) 20-25^o mid-crustal ramp that intersects iv) a wide northeast gently dipping that gradually passes into a sub-horizontal section of aseismic (creep) deformation (Figure 13-15). The MAT shows the double-ramp geometry with a flat detachment in between.

The Kruja thrust (KT) is the basal nappe of outcropped nappe stack. The mid-crustal ramp and the following eastwards MAT segment are consistent with the Kruja nappe. The location of the front of the high-level topography could be explained also by the mid-crustal ramp along the MAT. The down-dip mid-crustal ramp bends to merge with a sub-horizontal aseismic segment beneath the eastern domain in extension.

The geological building of Albanides as it is represented into the three MAT geological cross sections shows that its nappe pile can be divided into two plates: i) the Ionian fold-and-thrust basal nappe, affected by reverse faulting comprising the Albanides collision zone in compression, constitutes the lower plate, and ii) the Kruja nappe and overlying nappes, affected by normal faulting comprising the internal domain in extension, form the upper plate.

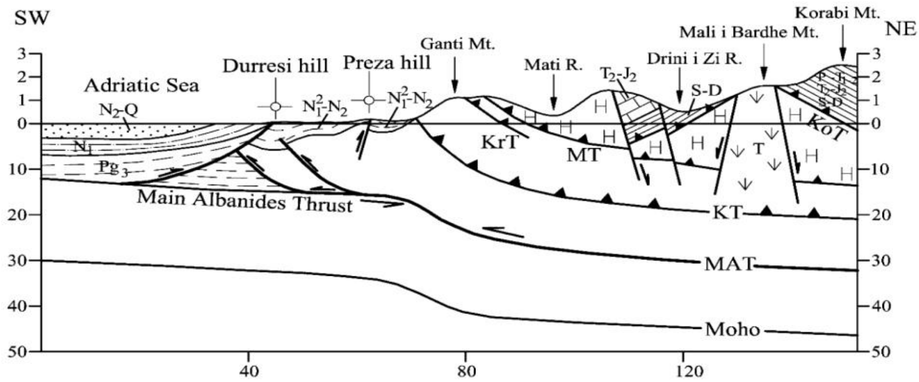

Fig. 13: Durresi hill-Korabi Mt geological cross section crossing South Adriatic Basin shows the fault geometry of the MAT that separates the Adria microplate underthrusting beneath the Albanides. MAT- Main Albanides Thrust, KT- Kruja Thrust, KrT- Krasta Thrust, MT- Mirdita Thrust and KoT-Korabi thrust.

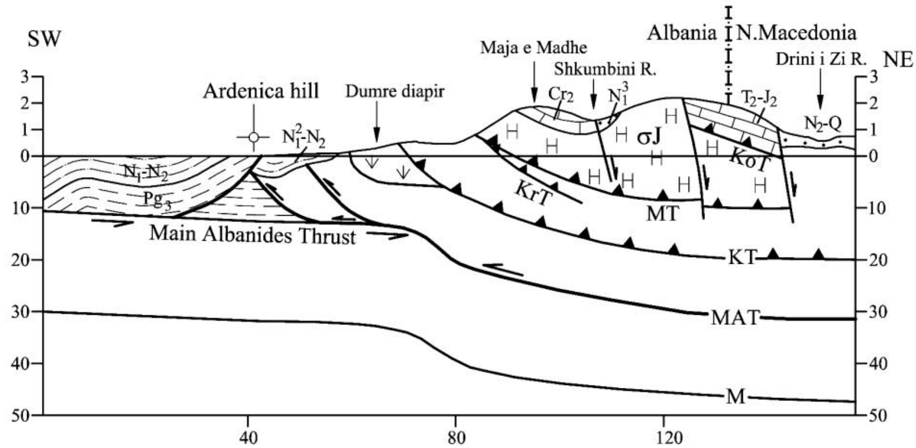

Fig. 14: Ardenica hill - Dumre diapir - North Macedonia border geological cross section crossing South Adriatic Basin shows the fault geometry of the MAT that separates the Adria microplate underthrusting beneath the Albanides. MAT- Main Albanides Thrust, KT- Kruja Thrust, KrT- Krasta Thrust, MT- Mirdita Thrust and KoT-Korabi thrust.

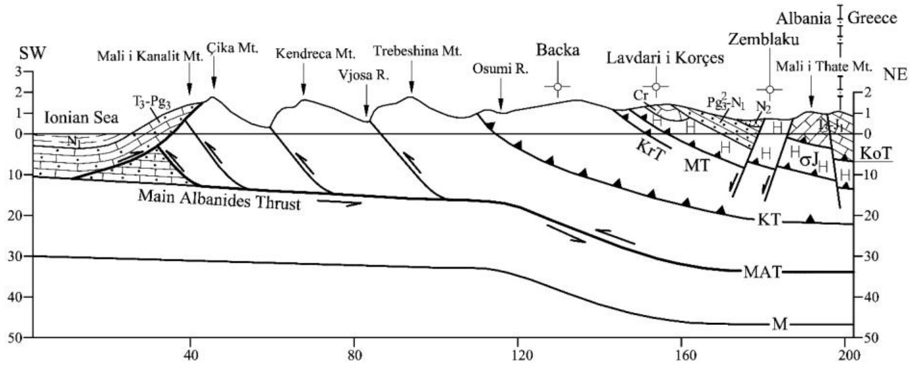

Fig. 15: Mali i Kanalit Mt - Mali i Thate Mt geological cross section crossing Apulian platform shows the fault geometry of the MAT that separates the Adria microplate underthrusting beneath the Albanides. MAT- Main Albanides Thrust, KT- Kruja Thrust, KrT- Krasta Thrust, MT- Mirdita Thrust and KoT-Korabi thrust.

Deformation of orogenic crust at Albanides during Tertiary occurred and occurs into both plate levels: i) a basal fold-and-thrust system in the Ionian Zone, that accommodated an increasing amount of SW directed shortening, and ii) a structurally higher system of normal faulting affecting the Kruja nappe and overlying ones, that underwent a strong structural rearrangement. Present-day convergence across the Albanides is mostly accommodated along MAT.

2. CONCLUSIONS

The following conclusions could be drawn: i) the present-day tectonics of the Albanides continental collision zone was investigated and the geometry of the main Albanides thrust was quantified based on the fault plane solutions for the November 26, 2019 Mw 6.4 Durres earthquake and other earthquakes events in Albanides collision zone. Here, the inferred geological and geophysical (seismic and gravimetric) data for the Albanides and separately for the Periadriatic Foredeep Basin were also used, ii) the Albanides-Adria collision thrust is divided into the north-west trending Lefkas-Corfu, and the generally north-south trending Dhermi-Durres segments through the Dhermi-Othoni Island and Drini Bay Lezha dextral transfer faults. A passage of the orogenic front from the Ionian Zone in the Adriatic offshore, south of the Drini Bay-Lezha dextral strike-slip fault, to the Kruja (=Dalmatian) Zone north of it, is assumed. The Dhermi-Durres segment is situated between the Drini Bay-Lezha and Vlore-Elbasan-Diber transfer zones. The Vlore-Elbasan-Diber transversal zone formed due to different direction of the Adria microplate compressional axes: towards northeast along the Lefkas-Corfu segment while towards the east along the Dhermi-Durres segment. It represents a dextral transfer zone characterized by plicate and disjunctive deformations that affect the tectono-stratigraphic units and molasses basins structures. The Dhermi-Othoni Island strike-slip fault can be considered the south-western segment of the Vlore-Elbasan-Diber long transversal zone. The displacements occur along the Ionian thrust front at Albanides and along the Kruja-Dalmatian thrust front at Dinarides, iii) the convergent boundary between the Albanides and Adria Microplate along the Dhermi-Durres segment follows the contact between Sazani and Ionian tectonic units up to Vlora city and then from Panaja through Frakulla to Durresi anticlinal line of quasi-northern extension it is deeply buried underneath the Middle Miocene-Pliocene molasses of the Periadriatic Foredeep Basin, iv) the seismic and geological cross sections passing through the Durresi hill (Adriatic offshore north of Durres), Ardenica hill (north of Fieri) and Llogora pass (25 km south of Vlora) demonstrate a significant face to face (tête à tête) collision between the Albanides and Adria Microplate. The seismic and geological cross sections passing through the Ardenica and Durresi hills show that thick Oligocene to Quaternary clastic sediments of the South Adriatic Basin (=Albanian Basin) are detached from their carbonate substratum through a detachment fault maybe at the base of Oligocene clastics and largely backthrusted onto the Ionian Zone frontal structures which are deeply buried underneath the Middle Miocene-Pliocene molasses of Periadriatic Foredeep Basin, v) an excellent seismic section passing through the Ardenica hill (north of Fieri) reveals the gently east dipping Cretaceous-Eocene carbonate substratum of South Adriatic Basin underneath the buried Ionian structures overlain by the Middle Miocene-Pliocene molasses of Periadriatic Basin. The top carbonate depths in the Adria Microplate are the followings: 12-14 km at Ardenica and Durresi hills, 3 km west of Sazani Island and about 4 km west of Mali Kanalit Mt. A mid-crustal low velocity layer between the depth of 5-7 km and 14-17 km is found along the coastal part of Albania (Periadriatic depression). This low velocity layer could be suggested to be the location of earthquake sources, vi) the focal mechanisms for the November 26, 2019 Durres earthquake and other earthquakes that occurred in the Albanides collision Zone fall into two categories: a) the low-angle thrusting planes NNW-SSE striking are restricted to a narrow belt of 20-25 km width following the Adriatic Sea coast along the Dhermi-Durres thrust segment, and b) the high-angle reverse faulting planes generally NNW-SSE striking are situated to the east of thrust faulting area, starting from the south of Dumre diapir with Berati anticlinal belt and southwards it enlarged with Kurveleshi and Çika anticlinal belts arriving the width of 60 km at south of Vlora (Llogora pass), and to the southeast of Dhermi-Othoni Island transfer fault along the Lefkas-Corfu segment it enlarged to 90 km width, vii) the fault plane solutions determined by various agencies for the November 26, 2019 earthquake and the focal plane solutions determined by GFZ for main shock and two aftershocks of magnitude greater than 5 of the November 26, 2019 earthquake show that they occurred on the NNW-SSE striking frontal blind thrust of low-angle dipping towards the east locating on the main basal thrust separating the Adria microplate underthrusting beneath the Albanides that is named the Main Albanides Thrust (MAT) and, viii) the November 26, 2019 Mw 6.4 Durres earthquake ruptured the two blind imbricate thrust-bounded faults that locate on the MAT highlighting its ramp and flat geometry. The fault geometry of MAT showing the double-ramp geometry with a flat detachment in between is represented by the Durresi hill - Korabi Mt, and Ardenica hill - Dumre diapir - Skenderbeu village - North Macedonia border geological cross sections crossing South Adriatic Basin, and by the Mali i Kanalit Mt - Mali i Thate Mt geological cross section crossing Apulian platform. The geological building of Albanides as it is represented into the three MAT geological cross sections shows that its nappe pile can be divided into two plates: a) the Ionian fold-and-thrust basal nappe, affected by reverse faulting comprising the Albanides collision zone in compression, constitutes the lower plate, and b) the Kruja nappe and overlying nappes, affected by normal faulting comprising the internal domain in extension, form the upper plate. Deformation of orogenic crust at Albanides during Tertiary occurred and occurs into both plate levels: i) a basal fold-and-thrust system in the Ionian Zone, that accommodated an increasing amount of SW directed shortening, and ii) a structurally higher system of normal faulting affecting the Kruja nappe and overlying ones, that underwent a strong structural rearrangement. Present-day convergence across the Albanides is mostly accommodated along the MAT.

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