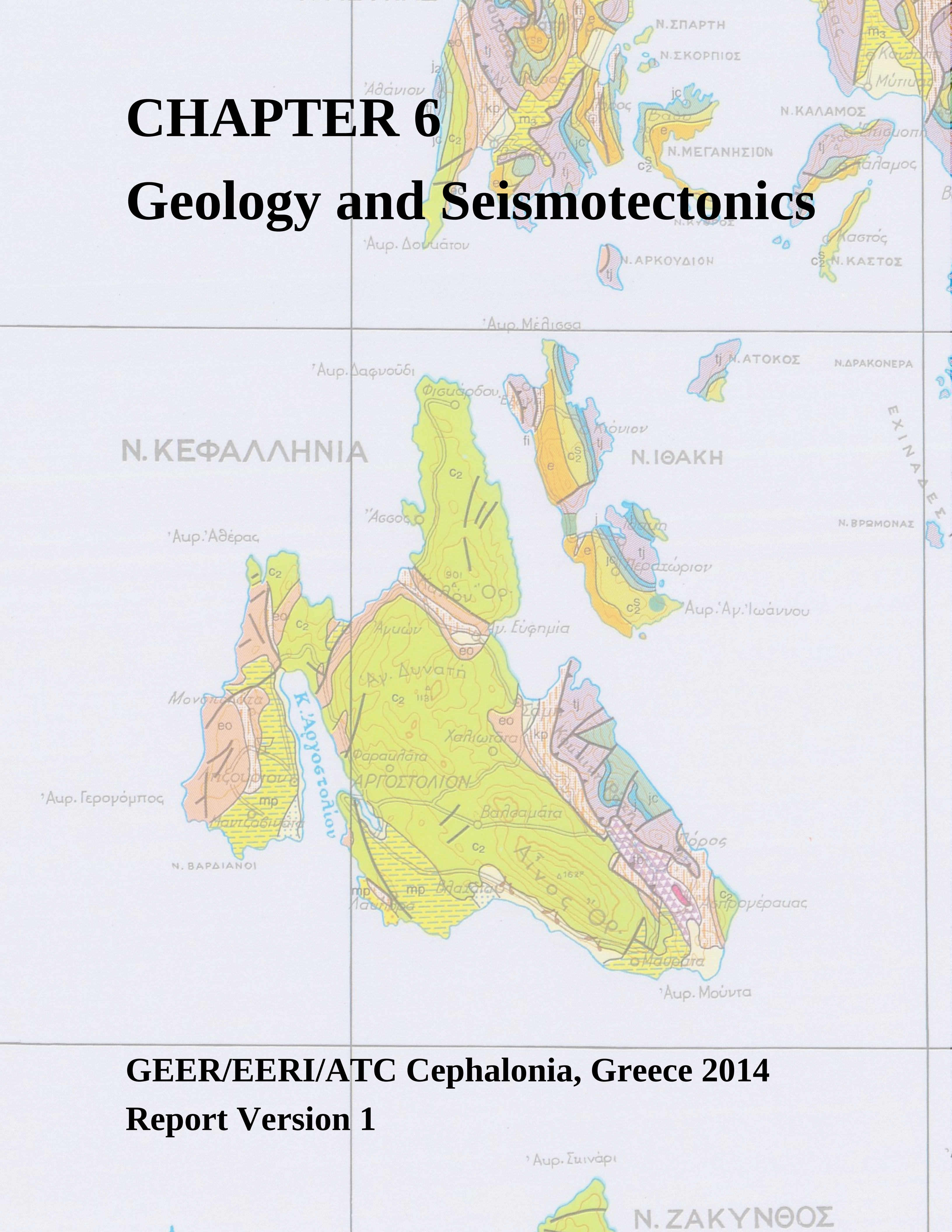
CHAPTER 6
Geology and Seismotectonics



GEER/EERI/ATC Cephalonia, Greece 2014

Report Version 1

6.1 Geology and Geomorphology

INTRODUCTION

The geological structure of Cephalonia Island is characterized by mostly carbonate rocks belonging to either the Pre-Apulian or Ionian geotectonic zones. An elongated post-Miocene basin, the remnants of which cover about half of the Paliki peninsula, interrupts the continuity of the bedrock formations. The geomorphology is characterized by Northwest-Southeast (NW-SE) trending morphological structures (ridges, valley, shorelines, etc.), attributed to the structural fabric of the island.

GEOLOGY

Cephalonia is located at the westernmost part of Greece. Geologically, the island is within the outermost edge of the External Hellenides zone (Fig. 6.1.1), which is an active part of the ongoing subduction of the African plate under the Eurasian one (Fig. 6.2.1).

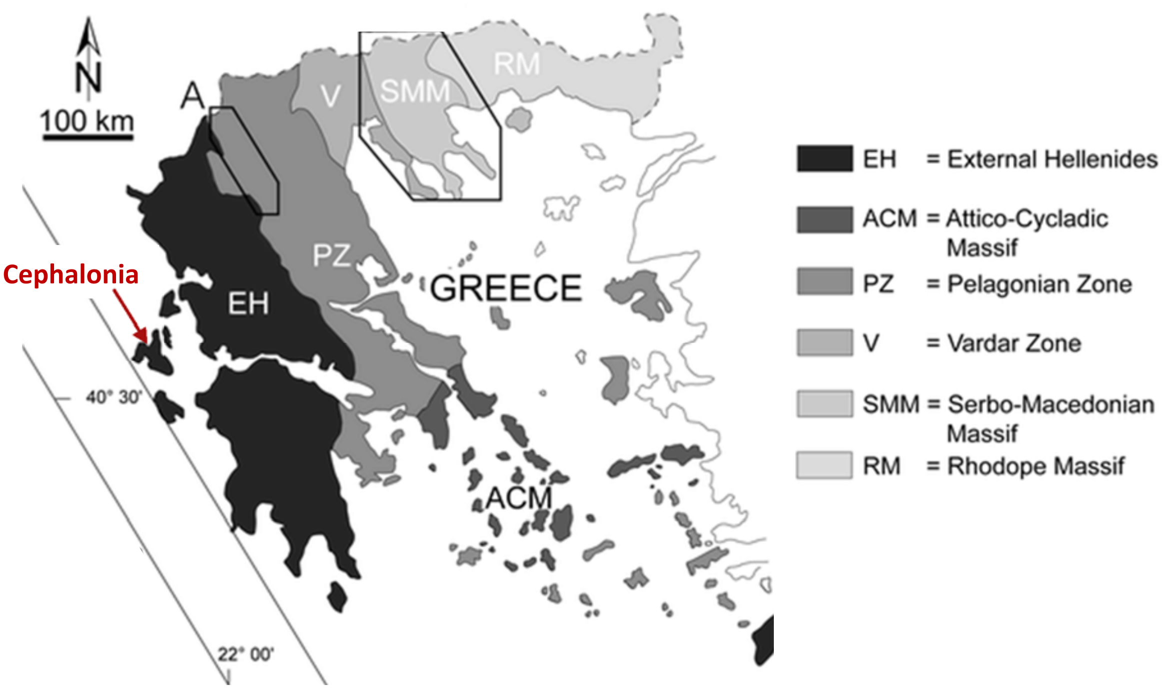


Figure 6.1.1. Geological zones of Greece including the External Hellenides zone which includes the island of Cephalonia (modified from Himmerkus et al., 2007)

The Hellenides zone consist the southernmost part of the Alpine mountain chain in Europe. The geotectonic evolution of this zone reflects the conditions associated with the closure of Tethys Ocean, a process still in progress to date.

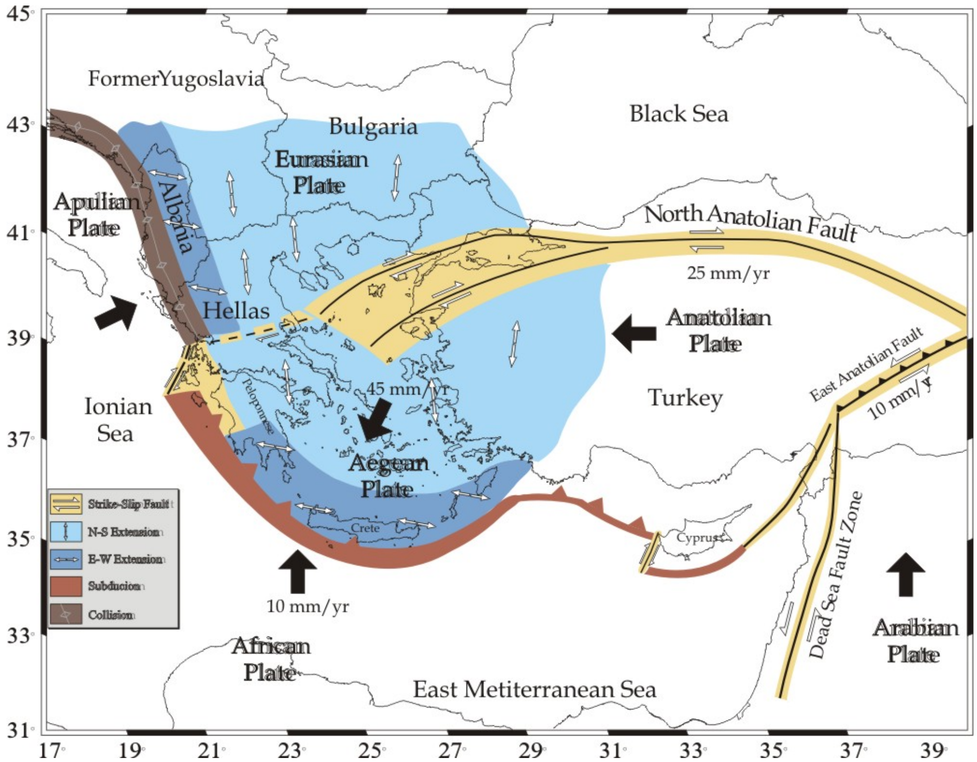


Figure 6.1.2. Simplified active plate tectonic activity. Black arrows indicate plate motions relative to Eurasia and small white arrows show direction of internal extension over the greater Aegean area (modified from Papazachos and Papazachou, 2003; also in GEER Report No. 013).

The formation of the Hellenides zone is mostly a result of the Alpine orogeny with the regional rock classified as pre-Alpine, Alpine and post Alpine ones, predating, concurrent and postdating the main orogenic phase respectively. The Hellenides zone of a general NNW-SSE trend (Fig. 6.1.1), divided into several geotectonic subzones, depending on the bedrock's age and formation history (Figs. 6.1.3, 6.1.4). In general, the geotectonic zones in Greece can be grouped into three distinct groups:

– Hellenic Hinterland: Paleozoic and Mesozoic crystalline rocks in NE Greece, representing the pre-Alpine bedrock. They have being intruded by granitoid Tertiary incursions and exhumed through a core complex mechanism.
– Internal Hellenides: Rocks with a wide range of age and origin that are considered to represent the remnants of Neotethys and Paleotethys Ocenas, i.e., ophiolites and associated sedimentary rocks, together with old crustal fragments forming the Pelagonian continental block. They are also intruded locally by granitic volumes.
– External Hellenides: In the outermost rocks of the Hellenic Arc, this group is the youngest sequence of Alpine rocks, exclusively of marine sedimentary nature. The age of the rocks typically start at Triassic and end with the deposition of flysch, whose age is gradually younger towards the West, indicating a gradual uplift.

Figure 6.1.3. Generalized map of geotectonic units of Greece. In general, the zones are younger moving towards West. The bedrock of Cephalonia consists of Ionian and Pre-Apulian Units (IGME, 1985)

Post-Alpine sediments overlie pre-existing Alpine and pre-Alpine rocks in basins, the most important of which is the Meso-Hellenic Trough, a wide and long NNW-SSE molassic basin in northern and central Greece. Many basins in Greece are f tectonic origin, being formed by neotectonic normal faults. It has to be noted that the term "post-Alpine" refers to sediments that have been deposited after the main paroxysmal phase of the Alpine orogeny. Since this phase is progressively younger toward the West, as the emergence ages show, this term is also applied in a different way in various parts of the Hellenides zone; a Miocene sediment for example is considered as post-Alpine in central Greece, while it is one of the latest Alpine members of the Pre-Apulian sequence in Cephalonia.

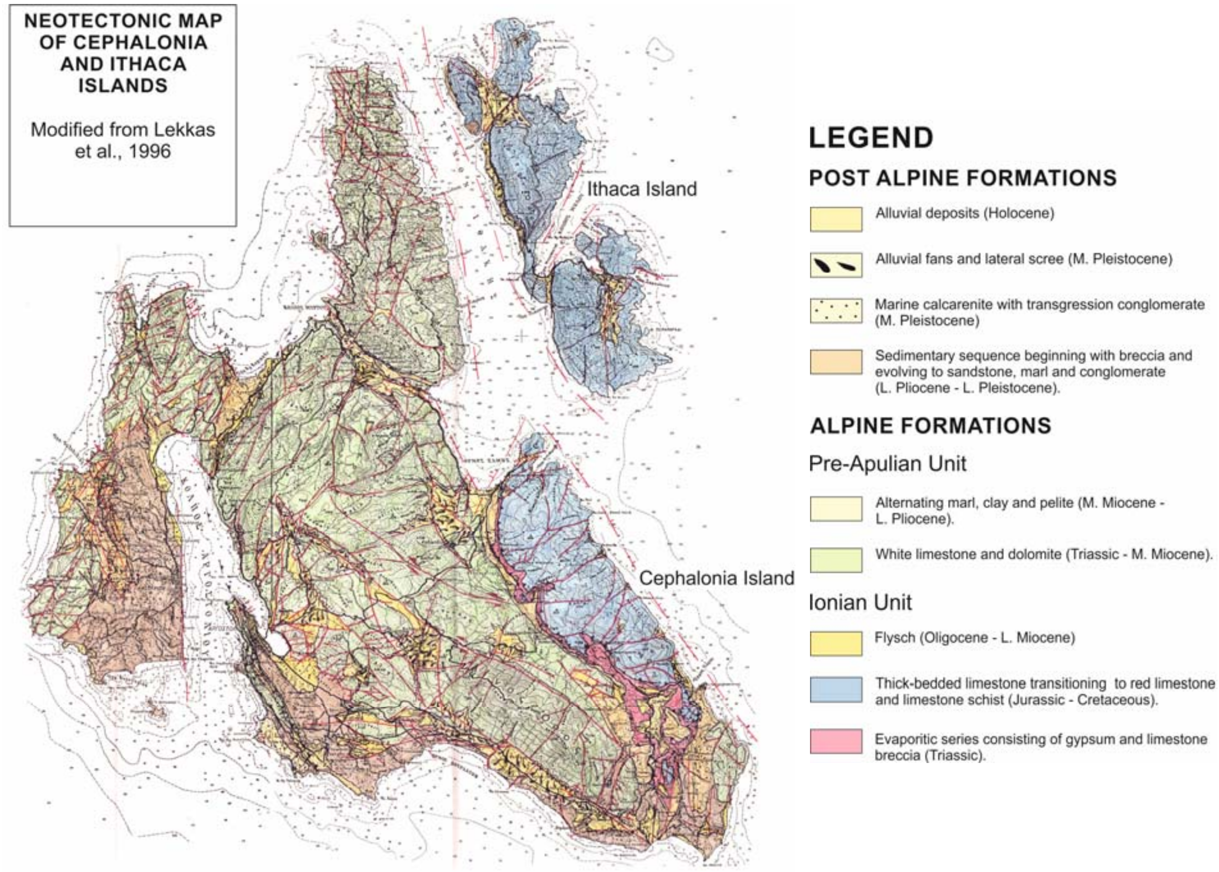


Figure 6.1.4. Neotectonic map of Cephalonia and Ithaca islands (modified from Lekkas et al., 1996).

The bedrock of Cephalonia Island mainly consists of carbonate rocks, divided into two units as shown in Figure 6.1.4:

1. Pre-Apulian (Paxos) unit: This rock unit covers most of the island, consisting mainly of a thick sequence of carbonates (limestone and dolomite) of Triassic to Middle Miocene age, overlain by a much thinner fine clastic sequence of marl and pelite of Middle Miocene to Lower Pliocene age.
2. Ionian unit. This unit covers part of the southeastern coastal areas of Cephalonia and the entire Ithaca Island. It also consist of carbonates of Jurassic-Cretaceous age, while their contact with the Pre-Apulian unit is defined by a frontal thrust of a general NNW-SSE direction. The lowermost part of the Ionian consists of a Triassic evaporite series that acts as “lubricant” for the thrusting.

The regional post-Alpine deposits are the following Pliocene to Holocene sediments units:

1. Lower Pliocene – Lower Pleistocene sedimentary sequence (Pl-Pt in Fig. 6.1.4) deposited in elongated basin in NNW-SSE direction, mostly of basal conglomerate, overlied by sandstone, marl and conglomerate covering most of the Paliki peninsula.
2. Middle Pleistocene – Marine calcarenite with a basal conglomerate, forming local coastal terraces.
3. Middle Pleistocene – Talus cones and lateral scree of cemented limestone blocks.
4. Holocene sediments – Fluvial loose sand and pebbles forming alluvial fans.

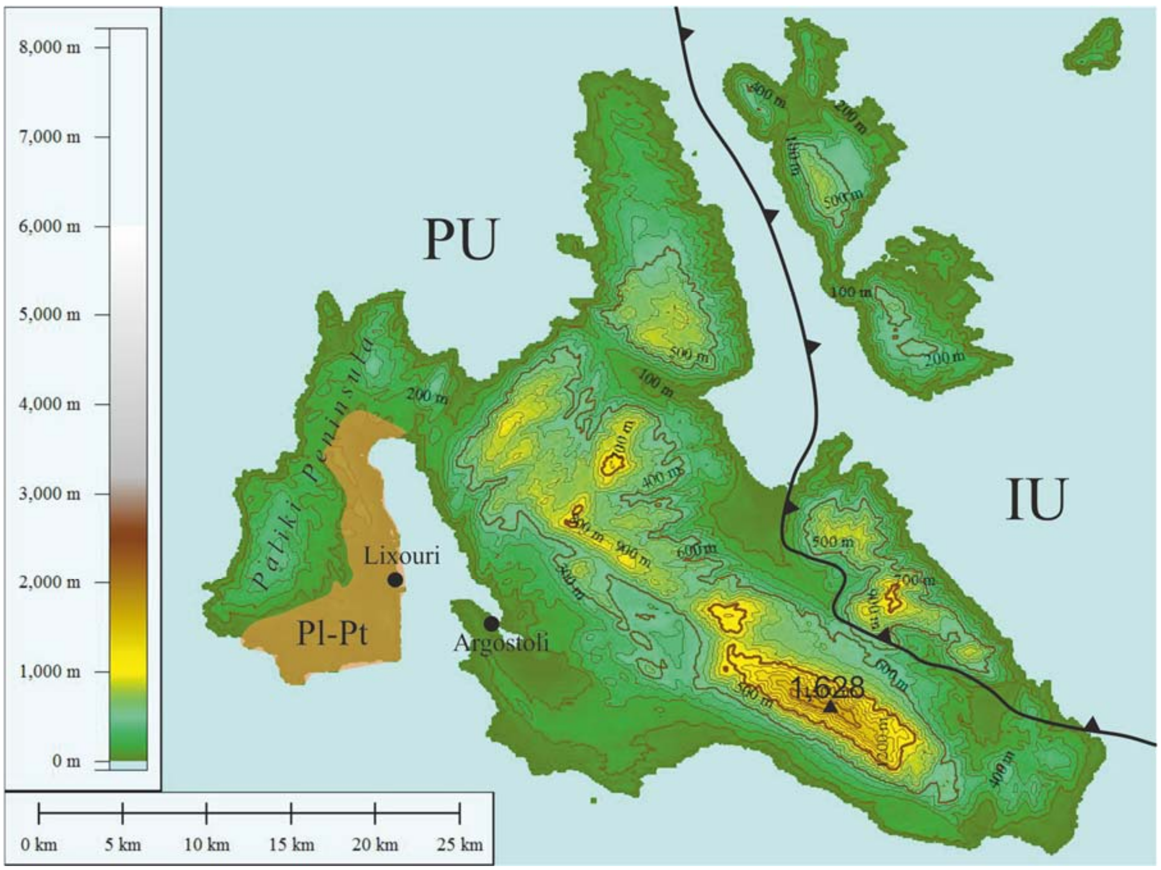


Figure 6.1.5. Topographical map of Cephalonia and Ithaca Islands, showing the main thrust separating the Ionian (IU) and Pre-Apulian Units (PU). The brown-shaded area (Pl-Pt) approximately marks the area covered by post-alpine (Lower Pliocene to Holocene) sediments in Paliki peninsula (IGME, 1985).

Most of the damage from the 2014 earthquakes was observed in the Paliki peninsula, particularly within the Lower Pleistocene sequence and on younger Holocene alluvial deposits. It is likely that the poor mechanical properties of these sedimentary sequences may have generated significant soil amplification effects. Liquefaction was observed almost exclusively in Holocene sediments, while rock falls and landslides occurred mainly in steep areas of carbonate rock slopes.

GEOMORPHOLOGY

The geomorphology of Cephalonia Island is characterized by steep bedrock slopes, especially along its western shoreline. Ridges are controlled by lithology and tectonics arranged in a NNW-SSE directions, the same as the dominant strike directions of the bedrock formations. The Paliki peninsula, the area hit hardest by the earthquake, is elongated peninsula and connects to the rest of the island at its northernmost part.

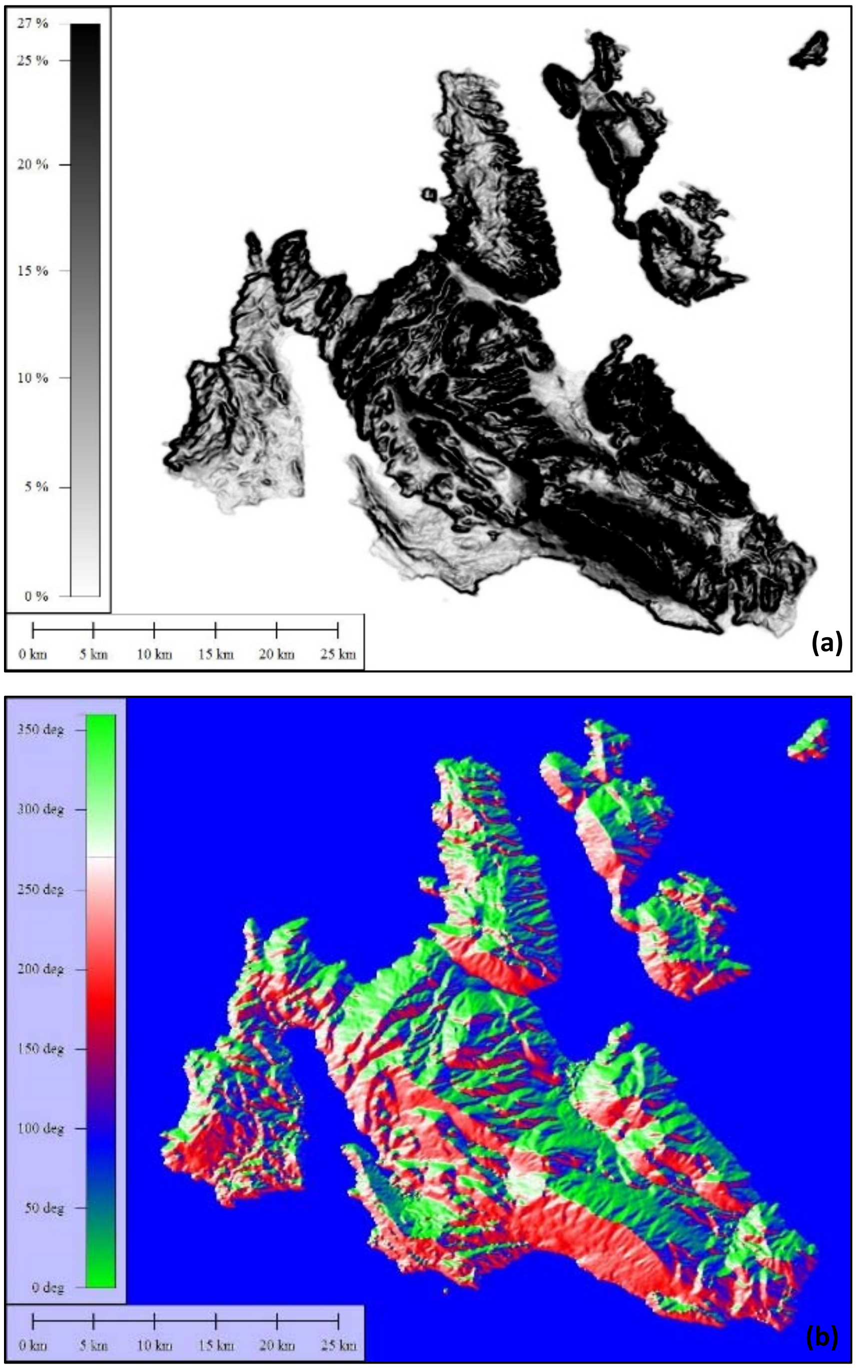


Figure 6.1.6. Cephalonia and neighboring islands: (a) slope map and (b) slope direction map.

FAULTING

Cephalonia is crisscrossed by faults of various directions and kind (normal, reverse and strike-slip ones), as shown in the neotectonic map of Figure 6.1.4. A well-documented offshore active fault known as CTF (Cephalonia Transform Fault) is in very close proximity as shown on Figure 6.1.7.

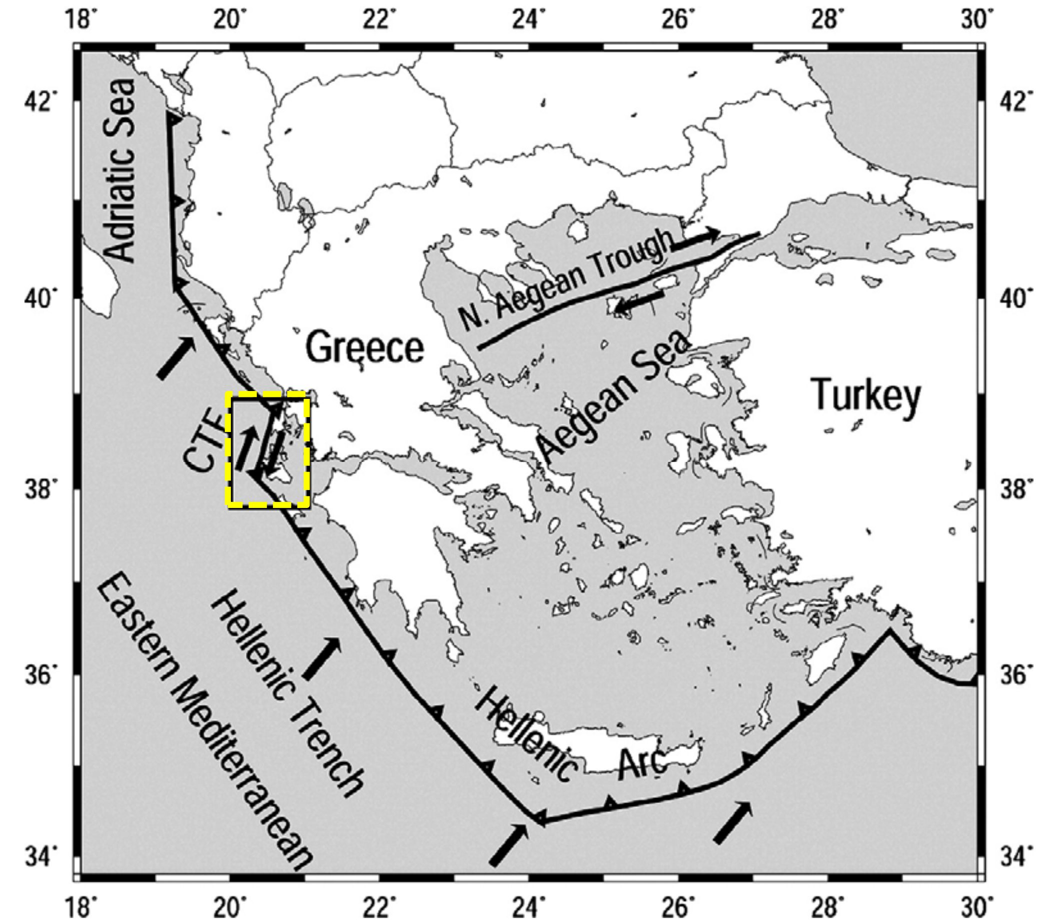


Figure 6.1.7. Main seismotectonic properties of the Aegean and surrounding regions. The study area is indicated by a rectangle. CTF = Cephalonia Transform Fault (modified from Karakostas et al., 2004).

The Greek Database of Seismogenic Sources (Gre.Da.S.S.) team has composed the main active fault zones in the area, presented in Figure 6.1.8. These zones are associated with known historical and instrumentally recorded large earthquakes. Their shape, direction and rake have been critically calculated from existing seismological and structural information. The seismogenic source GRIS 621, as identified by the Gre.Da.S.S. team in 2009, indicates a segment capable of generating a magnitude M_w 6.1 earthquake, similarly to the 1st event of January 26th, 2014.

The actual seismogenic area that includes the aftershock sequence and the 2nd main event of February 3, 2014, is also in good agreement in size with the computed one, but its location is shifted to the east. Chatzipetros et al. (2014) argue that this is a result of the pattern of faulting during the earthquakes, i.e., the activation of associated dextral and reverse faults, rather than the offshore zone itself. In any case, as field observations indicate, the causative faulting mechanism did not reach the surface.

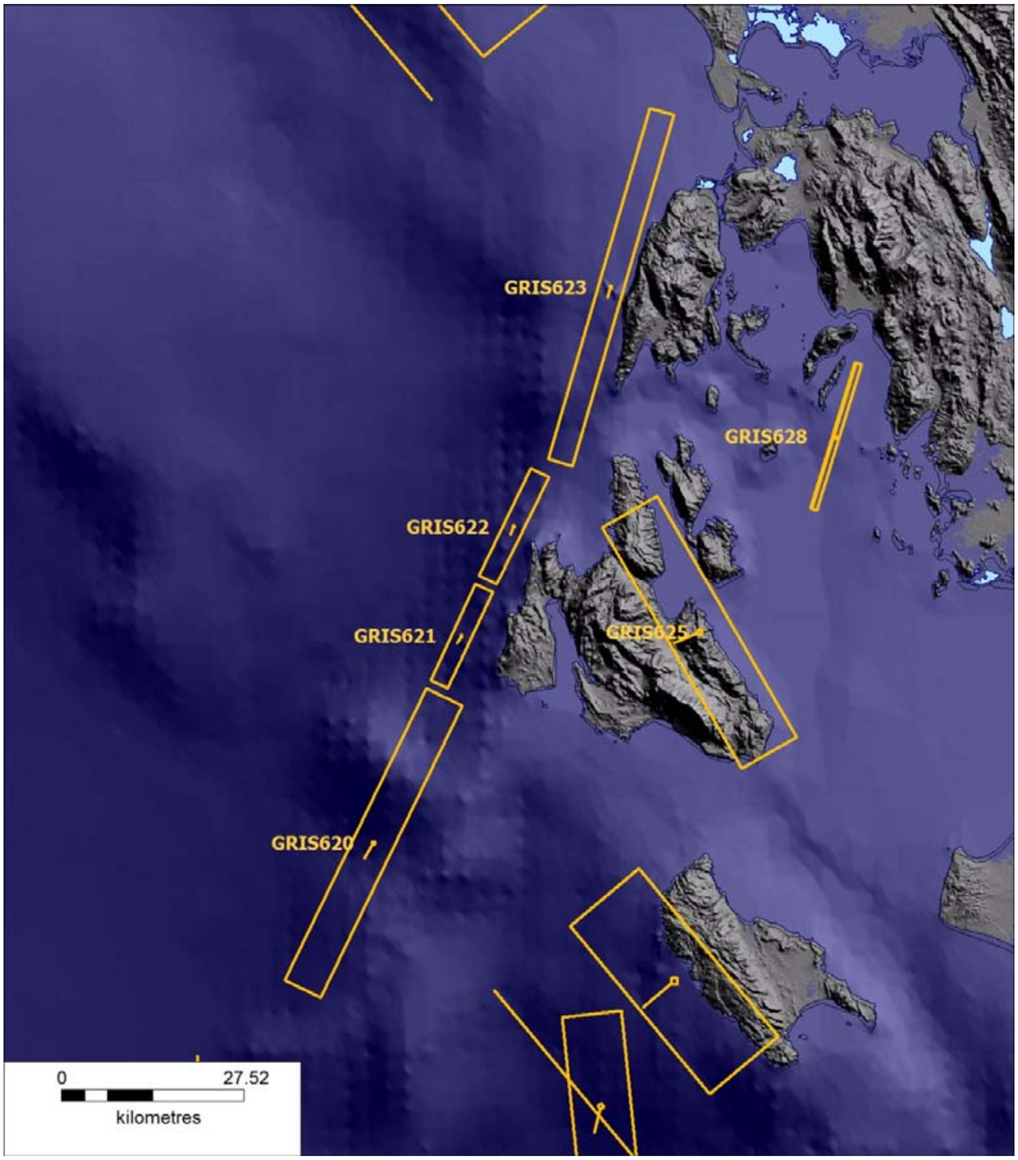


Figure 6.1.8. Seismogenic sources (i.e., active fault zones) in Cephalonia and surrounding areas, as mapped by the Gre.Da.S.S. team (Greek Database of Seismogenic Sources, gredass.unife.it). Yellow rectangular shapes represent surface projection of fault zones, and the arrows indicate the fault rake.

SEA RECLAMATION HISTORY

According to information provided by the local community, reclamation of the sea has been historically taking place after each large earthquake. Residents who had experienced the 1953 catastrophic earthquakes, recall that the material used for the reclamation was debris from the ruins left from these events.

Some background information is available for Argostoli, the capital and business center of Cephalonia since the 18th century, with a main port shown on Fig 6.1.9 at is original state. The city was destroyed from bombings during World War II in 1943 and the subsequent 1953 earthquakes. Recovery from these destruction took decades and was ongoing until the 1980s.

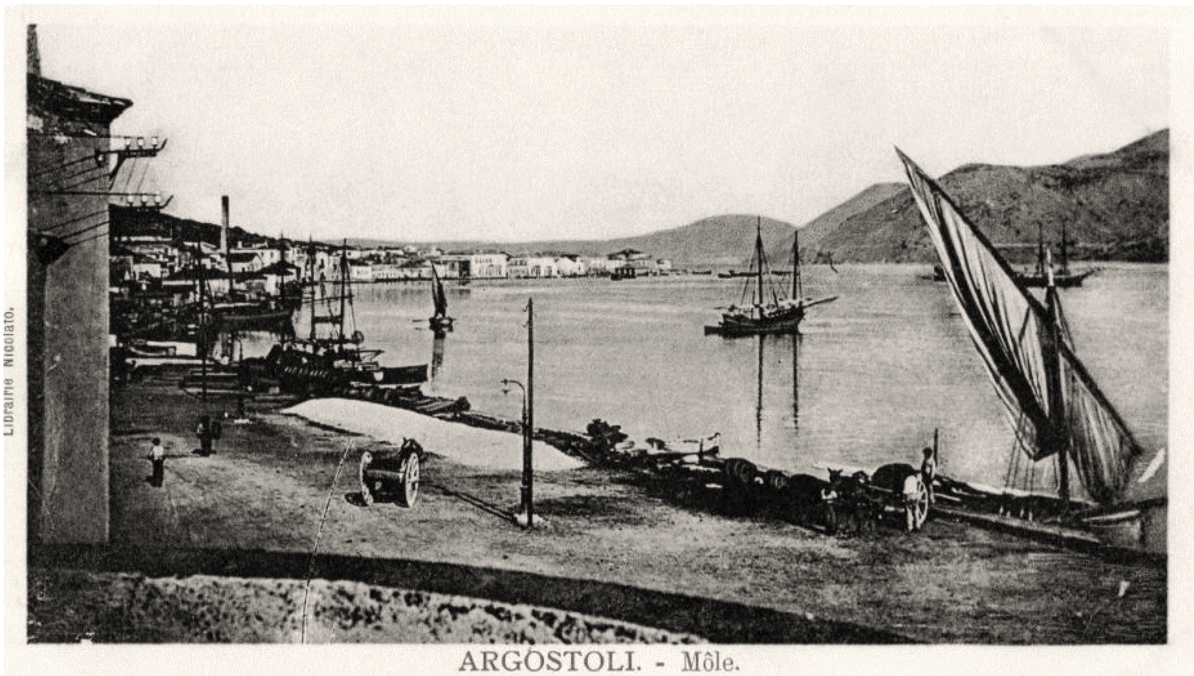


Figure 6.1.9. Argostoli port in 18th century (from ionian-island.co.uk).

Figure 6.1.10. Argostoli port in 1901 (modified from Pavlidis et al., 2010).

A virtual walkthrough of Argostoli before the 1953 earthquakes has been developed by Pavlidis et al. (2010), incorporating historic data on the urban development of Argostoli. Coastline of 1901 is shown on Fig. 6.1.10 and a 1949 topographic map is presented on Fig. 6.1.11. Aerial photos of 1940s and 2013 are shown on Figs. 6.1.12a,b, respectively.

Figure 6.1.11. Topographic map of Argostoli in 1948 (from Pavlidis et al., 2010).

Figure 6.1.12. Argostoli aerial photos in: (a) late 1940s (Pavlidis et al., 2010), (b) 2013 (Google Earth).

Based on our discussions with the local residents, the port of Lixouri was damaged in 1953 in a similar manner to that observed in 2014 (Fig. 6.1.13). The damaged seafront was demolished and then demolished materials together with the debris from damaged houses to extend the port area. The difference in the width of the port area is visible in Fig. 6.1.13. Further information will be provided in future versions of this report, as data on the sea reclamation history is under investigation by our contributors.

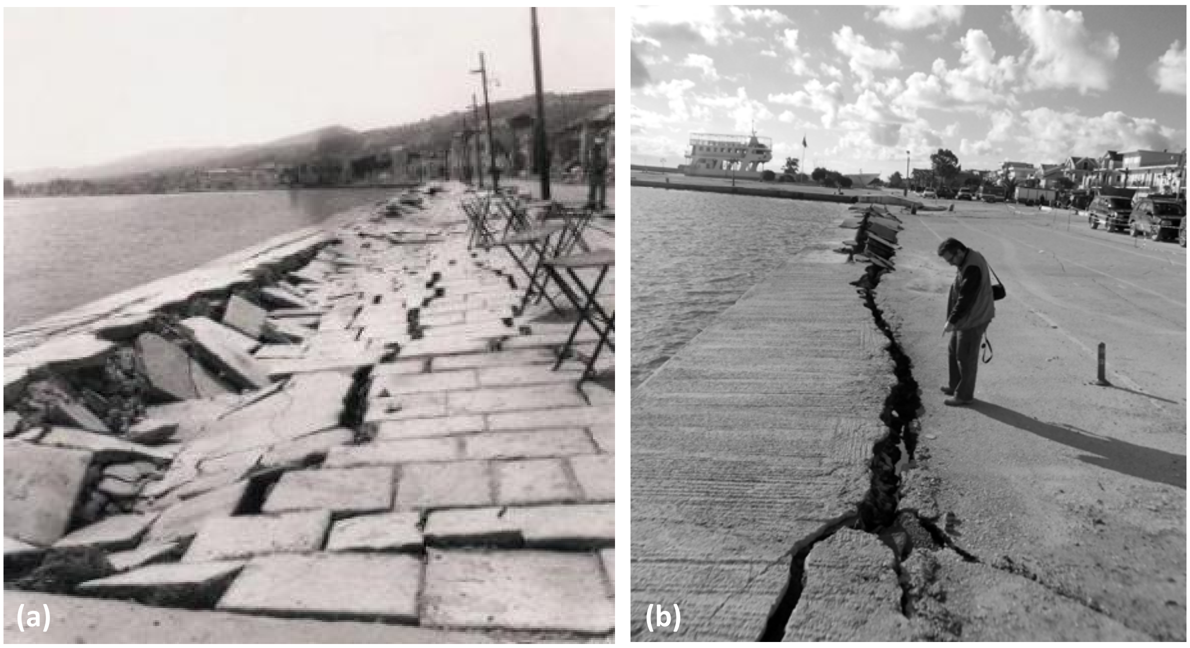


Figure 6.1.13. Lixouri port following the earthquakes of: (a) 1953 and (b) 2014.

6.2 Seismotectonics

Currently the seismotectonic mechanisms of the Cephalonia earthquakes are still under investigation. Specifically, there is uncertainty related to the geometry of the ruptured area that generated the two events, including the possibility of having a pair of closely-spaced parallel dextral strike-slip faults with a trust component that ruptured in a sequence, whose aftershocks are difficult to separate. Additionally, since the recording instruments are located in their vast majority on the east of the island, there is uncertainty regarding to the location of the epicenters. Some preliminary seismological information is provided in the next Chapter 7, primarily focused on the 1st M_w 6.1 event of 1/26/14. In this Chapter, remote sensing interferometry after the 2nd event is provided and currently being used to clarify the questions in the seismotectonic aspects of these earthquakes. The following issues under investigation will be addressed in the next version of this report: (i) magnitude and depth; (ii) activated fault; (iii) space-time distribution of relocated events; and (iv) fault plane solutions and stress-field.