Journal of Geography and Earth Sciences
June 2019, Vol. 7, No. 1, pp. 78-109
ISSN 2334-2447 (Print) 2334-2455 (Online)

Published by American Research Institute for Policy Development
DOI: 10.15640/jges.v7n1a9
URL: https://doi.org/10.15640/jges.v7n1a9

12,800 years ago, Hellas and the World on Fire and Flood

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Abstract

The controversial large cosmic impact hypothesis (~12,800 years BP) over the Northern Hemisphere explains not only wildfires everywhere but also the rapid cooling of the Younger Dryas by destabilizing and melting parts of the Laurentide and probably Fennoscandian Ice Shield; flooding large parts of North America and draining into the North Atlantic, which caused a slowdown or shutdown of warm water northward. The assumption of an impact origin of the approx. 20 km in diameter and only 100 m deep bowl-shaped size of the Holocene Pagasitic Gulf (Thessaly, central Greece), is based on a large negative gravimetric residual anomaly and Quaternary morphotectonic criteria along its shores, the shape of embankments and mountainous surroundings; such as collapse structures, slumping and landslides. Quaternary surficial cataclastic and brittle deformation from macroscopic to microscopic scale is present in many locations; e.g. micron size close-spaced planar fractures (PF's) in quartz and calcite. A modeled 1km comet with a density of 1500kg/m^{3}and an impact velocity of 50km/s fitted best all observed ground parameters, that generated airburst overpressures of 242 MPa causing cataclysmic wild fires and subsequent flooding.

Keywords: Comet airburst, Younger Dryas, Pagasitic Gulf (Greece), 12,800 years, Asteroid Impact

1 Introduction

The oral and written tradition of Greek mythology, dealing with natural catastrophes, explained in a spiritual and mystic way, is mind-blowing, since they show already a great knowledge about prehistoric times. Archaeological research has elucidated in great detail the Mediterranean history since Archaic times. Prehistoric and in particular the transition from Palaeolithic through Mesolithic to Neolithic periods still remain with many unexplained gaps and questions.

What was the reason for the lack of people during the *Bølling-Allerød* oscillation warming and the subsequent strong and sharp onset of the cooling effect of the Younger Dryas, together with the disappearance of large Pleistocene mammals like the woolly mammoth, starting at 12,800 years before present? No geological and archaeological findings that could explain realistically this problem exist in Greece.

The aim of the present contribution is to forward and test the provocative hypothesis that the Pagasitic Gulf was formed by a gigantic airburst of an asteroid or a comet, as part of the 12,800 years cosmic shower over the northern hemisphere, followed by fires and floods, which triggered the Younger Dryas. It should give possible answers about the missing links of the geological and historical evolution in the classical region of "Hellas" and wider surrounding areas during the critical time from Late Pleistocene to Early Holocene, e.g. the enigmatic gap to the rapid cooling and missing of a transition of anthropogenic and faunistic remains.

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The puzzle to achieve a logic sequence of events in the hypothesis is based on as much available scientific data, that is geological, petrological, chemical, isotopic, geophysical, oceanographic and climatic data, as well as on archaeological evidence. Also, a detailed account to the Tunguska airburst event 1908 in Siberiais also outlined, as a comparison to the final shape and structure of the Pagasitic Gulf.

1.2 The Younger Dryas in Europe

The rapid cooling of the Younger Dryas at 12,800 ± 150 years ago (Kinzie et al. 2017) is one of the most abrupt climate changes observed in Northern Hemisphere paleoclimatic records: □ ^{18}O composition in Greenland ice cores, varve microfacies in a volcanic maar lake, speleothems and mapping late-glacial and Holocene European pollen (Hartz and Milthers 1901; Brauer et al. 1999, 2008; Carlson 2013; Sadori et. al. 2016; Brewer et al. 2017).

A summary of the climate changes in relation to the chronology, □ ^{18}O data and sea changes during the Late Pleistocene and Early Holocene and correlated with archaeologic ages is represented in **Fig. 1**. The durations of the main archaeological ages appear in the lower portion of the plot, according to the general chronology (cf. Broodbank 2013), which demonstrates the time differences of their occurrences between south-eastern and northern Mediterranean regions. The oscillation of the *warm*interstadial "Bølling-*Allerød*"period in northern Europe between 14,800 and 12,800 BP (sharp onset of the Younger Dryas) is indicated by a period of approx. 500 years of sea level drop, whereas the beginning of the Younger Dryas appears only in the pattern of the Greenland ice core and the cave speleothems.

The Younger Dryas late glacial cooling period following the Pleistocene ice ages with a gap of a *warm,*2000 years lastingperiod in northern Europe is regarded today as a crucial time span, as it appears to be a bottle-neck in the development of mankind, the mysterious disappearance of early hunter and gatherer, which was followed by an explosive growth of agricultural settlements during Mesolithic period (Cummings et al. 2014), according to the north Mediterranean chronology, respectively to Neolithic period, according to the southeast Mediterranean chronology (**Fig. 1**). All over Europe and even in its southern parts the Younger Dryas showed strongly cold and arid conditions with an annual decrease of approx. 5-15 degrees Celsius, depending on altitudes (Tzedakis et al. 2004a and b; Carlson 2013; Seddon et al. 2015; Sadori et al. 2016; Benjamin et al. 2017).

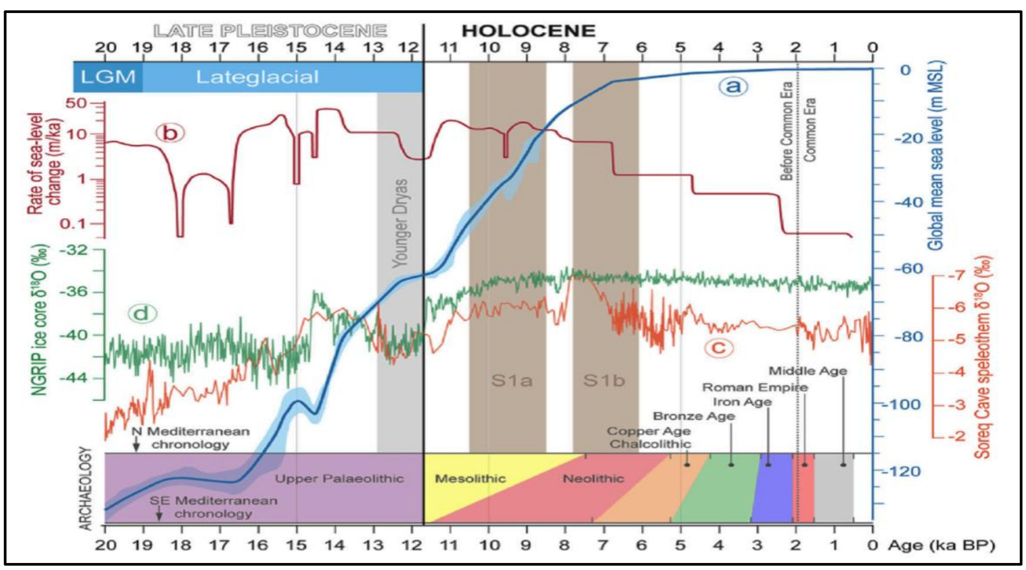


Fig. 1 Schematic correlation diagram during the past 20,000 years (Late Pleistocene and Holocene of the northern and south-eastern Mediterranean chronology from Upper Paleolithic to present day) between the reconstructed curve of global mean sea level (a), paleoclimate and paleoenvironmental data. In addition, the rate of sea-level change (b) with indication of the uncertainty shown in pale light blue (Lambeck et al. 2014); □ üp18O composition of the Soreq Cave speleothems (c); □ ^{18}O composition of NGRIP ice core (d) NGRIP members, 2017) is shown. Brown shading indicates the period of deposition of sapropels S1a and S1b (Rohling et al. 2015), which are dark layers rich in organic carbon and correspond to hypoxic or anoxic episodes of unknown origin. Credit to Benjamin et al. (2017).

During the cooling, vast areas of wild wheat and barley had allowed the first nomadic gathering-hunters in the Thessalian plains, as well as in the Middle East to establish permanent base camps. With the exception of a few caves, e.g. the Theopetra Cave in Thessaly (Facorellis et al. 2001; Kyparissi-Apostolika 2015), the Sarakenos Cave in Boeotia (Sampson 2008a), very little information exists from Mesolithic time from the Greek mainland. In contrast, Mesolithic sites are found in several caves close to the seaside (e.g. Franchti and Gioura), and on several Aegean islands (Ikaria, Milos, Naxos, Kythnos). Geological and bathymetric reconstructions indicate that still portions of the Aegean Sea, e.g. the Cycladic islands, have been subaerially exposed for most of the Late Pleistocene and acted as biogeographical land bridges (Kapsimalis et al. 2009; Lykousis 2009; Tourlokis and Karkanas 2012; Sakellariou and Galanidou 2015; Papoulia 2016). Therefore, it is not astonishing that during Mesolithic times gathering-hunters, fishermen and first nomads moved westward from Minor Asia and the Levant through the Aegean realm using possible land-bridges, as well as short sea ways and favorable currents to cross shallow channels with simple reed-bundle canoes and floats. In secure caves like Franchti on the Argolis peninsula, Magoulas on Kythnos and Cyclops on Gioura they created first local settlements of domestication (Sampson 2011). In addition, certain exchange trading might even has started with the most precious high-tech obsidian tools from the Melos in the Cyclades and Yali in the Dodecanese (Sampson 2014).

But the difficult climate conditions following the Younger Dryas cooling forced the earliest Mesolithic gathering-hunters to come together and work out first ways of maintaining the crops, through watering and selective breeding. Thus, farming began, allowing the rise of the first reinforced Magoula settlements. The hunted wildlife during the Late Pleistocene in the steppe of the Thessalian plains were similar to those of Eurasia and North America, which included large mammals such as the woolly mammoths, stephanorhinus, giant elk, the straight-tusked elephant and others. Fossils of this typical megafauna have been found in Peneios' lower terrace (NW of Larissa) and been dated to 45–30 ka (Demitrack 1986; Runnels and van Andel 1993a andb; Athanassiou 2011; Runnels 2014).

Similar slow changes followed during the cold and dry Younger Dryas climate, such as the transition from woodland to step on the northern hemisphere, which forced the survived inhabitants to start farming instead hunting and gathering. In the Aegean realm sea-level rise changed the landscape progressively, inundated coastal sites and changed fishing and shell fishing grounds. Existing islands disappeared; new islands and straits appeared (Benjamin et al. 2017). The onset of reforestation began around 12.4 ka BP, with different vegetation dynamics and woodland densities in the Greek mainland.

1.4 A Meteorite Impact as Trigger of the Onset of the Younger Dryas

An outstanding but controversial hypothesis on the origin of the Younger Dryas appeared in 2007. According to Firestone et al. (2007), a high-energy impact burst destabilized and melted parts of the Laurentide Ice Shield and consequently, flooded across large parts of North America and drained into the North Atlantic. Such a huge fresh water pulse might have caused a slowdown or complete shutdown of the North Atlantic Conveyor, which carries tropical warm water northwards and thus triggered the onset of the Younger Dryas (Broecker 2006), a rapid cooling with a temperature drop as much as 15^{o}C at the northern hemisphere. A sea-level change definitely has been recorded in many sedimentary sequences at this time period all over the world and in particular in the Mediterranean, as mentioned before by Sakellariou and Galanidou 2015 and Papoulia 2016.

After 37 years of intensive debate, the scientific community accepted the dinosaur extinction at the Cretaceous-Tertiary boundary 65 million years ago as a result of a very large asteroid impact (Alvarez et al. 1980 and 1982), while the Younger Dryas onset impact was likely the result of multiple impacts of a much smaller sized asteroids, maybe in the order of up to kilometer size projectiles. Up to now, there are three enigmatic circular objects in the northeast of the United States and Canada, which are possibly impact craters formed by fragments of a large object that hit the Laurentide Ice Shield or exploded in the atmosphere: 1) *The Charity Shoal*, a circular one-kilometer in diameter and 19 m deep basin in Lake Ontario (Holcombe et al. 2001); 2) *The Bloody Creek Crater* in southwestern Nova Scotia, a half-kilometer diameter and 10 m deep structure (Spooner et al. 2009); 3) The four kilometer diameter between 40 and 185 m depth *Corossol Crater* in the Gulf of St. Lawrence, Canada (Higgins et al. 2011). Except of the Charity Shoal structure, the Bloody Creek and the Corossol Crater were proven to have originated by meteoritic impact due to finding of high-pressure minerals and impact fabrics. In addition, recent geomorphological analysis of the Carolina Bays (US Atlantic coastal plain), using Google Earth images in combination with LiDAR data and testing with an experimental model, demonstrated their plausible impact crater origin formed on ground liquefied by the shock waves of secondary impacts of glacier ice bouldersejected by an extraterrestrial impact on the Laurentide Ice.

Sheet (Zamora 2017). The strange phenomena of the oblique conical craters, which had been interpreted by Firestone et al. (2007) as of extraterrestrial impact around 12,800 years BP, due to findings of ejected carbon spherules and vitreous charcoal, was highly rejected by many geologists. Very recently, a large impact crater has been found beneath the Hiawatha Glacier in northwest Greenland (Kjær et al. 2018). The age of the 31-kilometer-wide and up to 1000m deep crater has been estimated according heavily disturbed Pleistocene ice overlying Precambrian basement, as well as to the continuous and conformable Holocene ice sheet cover as close to 13,000 years BP. The authors imply that such a large crater must have been formed by an impact of an approx. 1km iron asteroid.

The worldwide effect of a meteorite shower covering a strewn field over the Northern Hemisphere (**Fig. 2**), estimating more than 50 million square kilometers, may have triggered the onset of the Younger Dryas and causing wildfires everywhere, as well as rapid cooling (Wittke et al. 2013; Wu et al. 2013; Kennett et al. 2015; Kinzie et al. 2014). As result of extensive atmospheric soot and dust, the *warm*interstadial "*Bølling-Allerød"*period turned rapidly into the «impact winter» of the Younger Dryas sustained by the break off of major ice masses from the Laurentian ice shield and blocking warm Atlantic currents toward north. Wolbach et al. (2018a and b) reinvestigated all available evidence of such hypothetical cataclysmic scenario compiling quantitative analyses of charcoal and soot records from 152 lakes, marine drill-cores and terrestrial sequences that testify large wildfires and biomass burning. Napier and Cube (1997) already suggested that the Earth is in a state of "coherent catastrophism" since 20 to 30 thousand years ago. A large progenitor of the Enke comet with an estimated diameter of more than 100 km might have entered the solar system orbiting the Sun. Fragmentation due to an eccentric movement around the sun generated an orbital ring of debris intersecting the Earth's path, which resulted in meteorite showers, the "Southern and Northern Taurids", known since historical times. A several kilometer large fragment from the Taurid stream, entering the Earth's atmosphere, most probably was disintegrated with multiple airbursts and impacted with high energy on the Earth's surface all over the Northern Hemisphere (Napier 2010; Napier et al. 2015).

Despite many inconsistencies of the impact hypothesis, in particular concerning the physics of airbursts (Boslaugh et al. 2013), geological evidence of such a catastrophic event is demonstrated by the dispersed glassy silicate and carbon spherules and nanodiamonds in the order of 10 million tons containing micron sized zircons and rutile, high-temperature melted glass, a wide spread platinum anomaly and occurrence of nanodiamonds (**Fig. 2**) in eleven archaeological sites across North America (Bunch et al. 2012; Moore et al. 2017) and in the Greenland ice (Kennett et al. 2009; Kurbatov et al. 2010).

Fig. 2 Map showing 24 sites containing Younger Dryas Boundary (YDB) nanodiamonds. The solid line defines the current known limits of the YDB field of cosmic-impact proxies, spanning 50 million km², including Venezuela (open circle). Numbered sites are from this study: 1) *Lake Cuitzeo, Mexico*;2) *Daisy Cave, California*;3) *Arlington Canyon, California*;4) *Murray Springs, Arizona*;5) *Lindenmeier, Colorado;* 6) *Bull Creek, Oklahoma;* 7) *Blackville, South Carolina*;8) *Topper, South Carolina*;9) *Kimbel Bay, North Carolina*;10) *Newtonville, New Jersey*;11*) Melrose, Pennsylvania;* 12) *Sheriden Cave, Ohio*;13) *Gainey, Michigan*; 14) *Chobot site, Alberta, Canada*; 15) *Lake Hind, Manitoba, Canada*; 16) *Kangerlussuaq, Greenland*; 17) *Watcombe Bottom, Isle of Wight, United Kingdom*;18) *Lommel, Belgium*; 19) *Ommen, Belgium*; 20) *Lingen, Germany*; 21) *Santa Maira, Spain*; 22) *Abu Hureyra, Syria*. In addition, independent researchers have reported NDs at six sites, indicated by letters, four of which are in common: a) *Indian Creek, Montana*; b) *Bull Creek, Oklahoma*; c) *Sheriden Cave, Ohio*; d) *Newtonville, New Jersey*; e) *Lommel, Belgium*; f) *Aalsterhut, Netherlands.* Credit to Wittke et al. (2013); Kinzie et al. (2014).

A "black mat horizon" containing nanodiamond polymorphs mixed with "glass-like" carbon microspherules dated 12,900 years ago has also be recognized in North America (Kennett et al. 2015). The instant "megafauna or mammoth extinction" seem to have commenced also at this time maker, but continued certainly over the entire Younger Dryas period, which ended 11,703 ± 4 BP (Holliday et al. 2014; review in Rasmussen et al. 2014). Convincing evidence of a large impact that might have been responsible for the onset cooling of the Younger Dryas has been found in Greenland ice core dust (GISP2) associated with a large Pt anomaly spanning over 21 years (12,836-12,815 BP, Wolbach et al. 2018a), which is interpreted as result of a large Ir-poor iron meteorite shower (Petaev et al. 2013).

Benchmarks for the existence of the cosmic cataclysm in Europe and Asia at 12,800 years BP are the archaeological findings of the settlement Abu Hureya in the Euphrates valleys, one of the "birthplace of Agriculture", which lasted from around 13,500 BP and continued with intervals for several millennia thereafter until the end of Neolithic at least 5000 years BP (Moore et al. 2000; Mithen 2006).

Soil samples contained a high amount of glass spherules of 20-50mm and vesicular, scoria-like objects (SLO)>5.5 mm, which are composed of amorphous SiO_2 (lechatelerite) mixed with CaO-rich glass. Moore and Kennett (2013) claimed these features as result of melting underground sediments caused by a high-energy air-burst/impact in the vicinity of Abu Hureyra (northern Syria) at around 12,800 years ago. Other evidence has been found in ancient symbolic stone carvings, which are interpreted as Taurid observations and a comet swarm hitting the Earth (Sweatman and Tsikritis 2017). This "world's oldest known temple" with its pillars, Göbekli Tepe (SE Turkey) is thought to have been built around 12,000 years BP (Dietrich and Schmidt 2010; Dietrich et al. 2013).

Since witnesses of such a cosmic cataclysm exist in Minor Asia and many indications repeatedly appear in the Greek mythology, it is obvious to search for further substantial locations of cosmic remnants in Greece.

1 Pagasitic Gulf, a Possible Complex Impact Crater

According to the Hellenic myth, *Zeus hurled a thunderbolt down to earth from the throne of gods, Mount Olympus, to destroy Phaethon, the son of Helios, and* "*burnt up all that was upon the earth" (Plato's Timaeus).*Despite the ancient myth, there is always a reality, a kern of truth hidden behind. Not far south from the "site of the divine punishment" lays the Pagasitic Gulf (Pagasitikos Kolpos), an approximate 20 to 25 km large irregular shaped circular shallow gulf that is connected with the Evoic Sea to the south through a 4km wide channel, the Trikeri Strait (**Fig. 3**). The large sickle-shaped Mount Pelion Peninsula separates the gulf from the North Aegean Sea to the West and South. The eastern shores of the gulf are bordered by the foothill extensions of the Orthris Mountains and the conical shaped alluvial plain of Almyros, while the northern shores border the Nea Anchialos mountain range in the western part, and the Volos Bay and plain in the eastern part.

The bowl-shaped geometry of the gulf, the inclination of all embankment lithologies towards the gulf and in particular the unusual and unique morphology and structural features that evolved from the 3D Google Earth images, as well as the recognition of abundant regolithic and weakly cemented brittle surfaces along the shores and hill sides, led to the assumption that the bowl-shaped gulf may have been formed by an impact, either by a meteorite or by high-pressures of an air-burst, probably contemporaneous with the Zerelia Twin Lakes (Dietrich et al. 2017). The proof of such large catastrophic event at the beginning of the Holocene would underline the Younger Dryas Impact Hypothesis and help to explain the spatial and temporal distribution of mankind in southeastern Europe, between the Paleolithic, Mesolithic and Early Neolithic.

A prerequisite of understanding the observed unusual young deformational structures around the Pagasitic Gulf is the discrimination of similar features, as results of older geological and tectonic events. They are part of the supplements and designated to describe the geotectonic and morphotectonic framework, as well as the geological and lithological characteristics in detail.

2.1 Bathymetry of Bowl-Type Gulf

The bathymetry of the Pagasitic Gulf (**Figs. 3 and 4**) comprises the form of a shallow bowl with a depth of about 100m and an asymmetric deeper seafloor in the eastern part (Perissoratis et al. 1991 and Petihakis et al. 2012). Lacustrine and marine unconsolidated sediments reach maximum thickness of approx. 100m. Many fluvial-torrential terraces (e.g. loose conglomerates, sand, silt and clay with low percentage of coarse-grained material) occur in several areas. Holocene scree and large talus cones are developed at places along the eastern coast (e.g. in the deltas of Agria, Lechonia, Kala Nera and Kalamos).

Fig. 3 Google Earth image of the Pagasitic Gulf – Mt. Pelion area; bathymetry according to Perissoratis et al. 1991; Korres et al. 2011; Petihakis et al. 2012. *The Zerelia Twin-Lakes* on the western side of the image (Dietrich et al. 2017). Image: Digital Globe Google Earth.

Fig. 4 Overview Pagasitic Gulf from Aghios Georgios towards south; below the coastal village of Kato Gatzea. Photo V. Dietrich

According to regional reconstruction, a marine ingression, which led to the manifestation of the Pagasitic Gulf, allows only speculation, but has been estimated as Early Holocene (Van Andel and Perissoratis 2006; Sakellariou and Galanidou 2015). A certain calibration can be made, comparing the oceanographic and sedimentary results in the western basin of the North Evia Gulf (Sakellariou et al. 2007) according to high-resolution sub-bottom profiles and gravity coring.During the last glacial period the water level of the North Evia Gulf was about 90m below the present sea level with lacustrine sediments that were formed during the last glaciation. In addition, this thick sedimentary sequence was covered by a prominent unconformity, which was topped by a thin marine sedimentary sequence. This interpretation leads to a major tectonic movement accompanied with a dramatic rapid uplift of the region, most probably during the Pleistocene/Holocene boundary. We tent to relate this rather rapid feature with a catastrophic event in the Pagasitic environment. In contrast to a rapid process, the region of the Almyros plain and Pagasitic environment seem to have been rather stable besides local earthquake activity along the Almyros and Anchialos fault zones (Caputo and Pavlides 1993; Papazachos and Papazachou 1989). This has also been proven by the stable coastlines of the Pagasitic Gulf (Galanakis et al. 1998), which indicates the absence of any differential uplift between the Aegean Sea level and the surrounding mountain chains since early Holocene time.

2.2 Morphotectonic and Surface Structures of the Gulf Surroundings

At first glance, the sickle-shaped Pelion Mountain range towards East, the Trikeri Peninsula to the South, the Kokkinovrachos range in the Southwest, the conical shaped alluvial plain of Almyros in the West and the Nea Anchialos mountain range in the North form today an irregularly shaped rim around the Pagasitic Gulf shallow marine basin. Nearly at all places, the coastal rocks plunge towards the sea at low inclination with angles between 10 and 30 degrees.

2.2.1 Slumping and Landslides

The use of high-resolution and 3D imaging Google Earth reveals another remarkable geomorphological feature. Many mountain slopes around Pagasitic Gulf exhibit a step-like landscape, which can be explained as a result of special feature of a mass wasting collapse structure, e.g. slumping or landslide, which are designated depending upon their size mainly between several tens of meters up kilometer size (**Figs. 5-7**).

Slumping is a linear to sickle shaped, mostly planar scarp that usually parallels an elongate ridge and faces uphill. A typical characteristic feature is the valley behind the scarp, which has the morphology of an asymmetric neck, a neck-type valley with a steep wall downhill and a gentle wall uphill (**Figs. 5 and 6**). In general, this morphological feature may on first examination appear to be young tectonic features and has been used to interpret its origin due to earthquakes. In high-altitude glaciated mountainous areas, slumping has also been recognized as post-glacial features.

Fig. 5
Landslide and slumping morphology with neck valleys in the western Mt. Pelion slopes; village of St. George Nilias in the foreground; view towards northwest. Photo V. Dietrich.

Fig. 6 Landslide and slumping with neck valley morphology in the southwestern slopes of Mt. Pelion, from west of Pinakates; view over Pagasitic Gulf towards south. Photo V. Dietrich.

Generally, slumping or a landslide occurs as movements of large masses of earth and rocks down a hill or a mountainside. Little or no flowage of the materials starts on a given slope until heavy rain and resultant lubrication by the same rainwater facilitate the movement of the materials, causing slumping to occur. Slumping on local scales and landslides on larger scales can also start spontaneously by a shock, such as an earthquake or as slow movements over timespans of several years. Requirements are more or less planar unconformities between lithological units and preexisting fractures and faults, which provide circulation of water. In addition, often lithologies with physical properties predestined for alteration and argillitization turn into lubricant horizons.

2.2.2 Listric Faults and Collapse Structures

In the case of the Pelion situation as well as in other, the Pagasitic Gulf surrounding mountainous areas, the intensive pre-Neogene Alpine thrust sheet tectonics of the Pelagonian nappes with the predominant content of highly tectonised overthrust horizons, consisting of mylonitized slates, phyllites, schists and serpentinites facilitate the landsliding and slumping capability (**Fig. 7**).

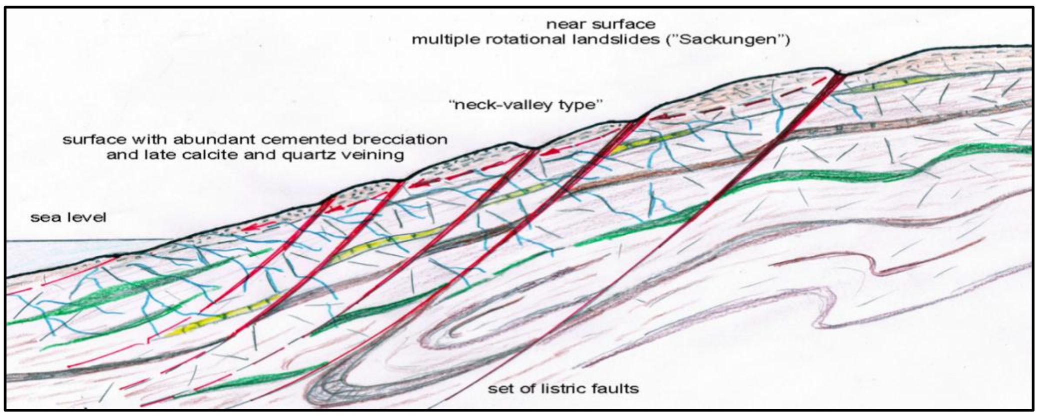


Fig. 7 Morphotectonic interpretation of landslides (slumping) turning into sets of listric faults in the Mt. Pelion western slopes. The Holocene surface is covered with abundant cemented breccia cross cut by late calcite and quartz veins.

Surface ruptures, which crop out at the surface as more or less vertical steep scarps seem to have turned into listric faults, starting with a steep inclination surface and rotating to a shallower dip with increased depth. The dip may flatten into a sub-horizontal décollement, resulting in a horizontal displacement.

These structures have been recognized in many places in the mountainous surroundings of the Pagasitic Gulf with general inclinations of the lithologies towards the gulf. Because of the consistency, we interpret them as collapse structures related to a contemporaneous event.

2.2.3 3D Fault Pattern Observation

Detailed observation using Google maps and enlarged 3D Google Earth images reveal many faults in the coastal and mountainous surroundings of the Pagasitic Gulf, which cannot be recognized in the conventional way from the surface(**Fig. 8)**.

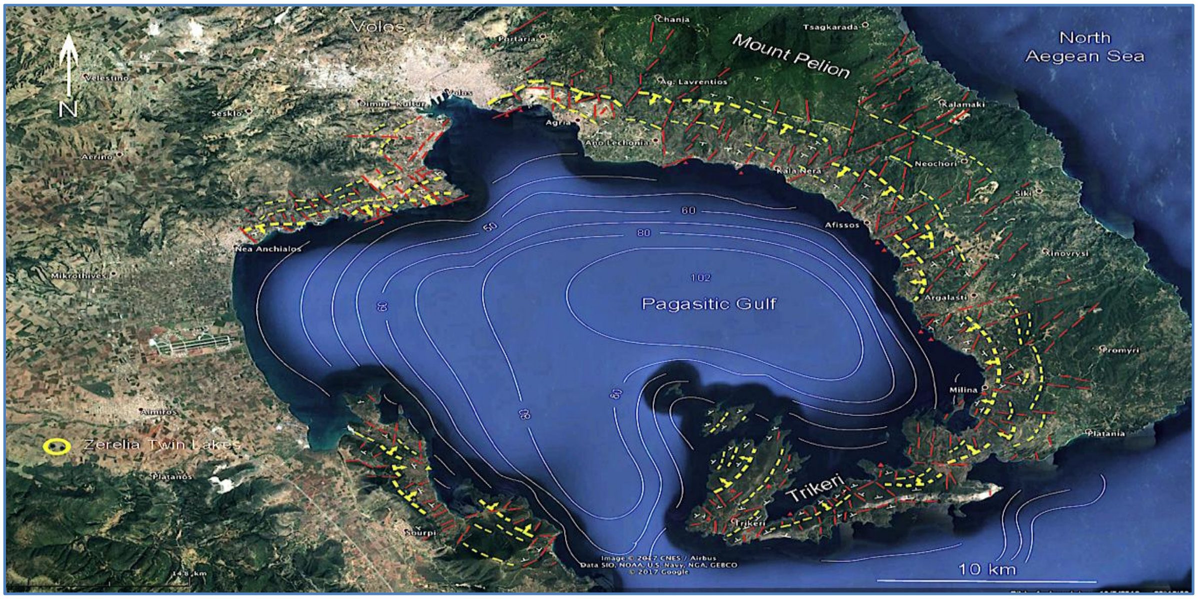


Fig. 8 Morphotectonic map with localities of major breccia (red triangles) and cataclastic deformation around Pagasitic Gulf, a compilation of rotational landslides (surface slumping and listric faults in yellow) with radial normal and strike/slip faults in red), all dipping towards the gulf; strike and dip signs were taken from map sheets 1:50 000 Geological Map of Greece (Katsikatsos et al. 1978, 1987, 1989; Marinos et al. 1957, 1962). Red triangles are locations of major breccia occurrence; image: Digital Globe Google Earth.

These are sets of normal steep faults causing narrow gorges and valleys and run more or less perpendicular to the directions of the landslide morphology). Of course, the larger normal and strike-slip faults systems that was recognized as pre-Holocene of age and due to historical earthquake activity is apparent and marked, too. In the Pelion Mountain range, the Trikeri Peninsula and the Kokkinovrachos range, the E-W and different NE-SW fault directions are dominant, whereas in the Nea Anchialos – Cape Agistri Range a NW-SE fault pattern is evident. However, it is difficult for most of them to establish a recent reactivation. In general, the sum of all fault-sets leads to an impression of a certain radial appearance pointing towards the gulf.

2.3 Surficial Cataclastic and Brittle Deformation

Evidence of a meteoric impact is normally given by pressure and temperature effects on the underground of the impact site, e.g. on rocks and soil inside the impact crater, the distal environment and the occurrence shock-infected or molten ejecta. In the case of a possible impact forming the Pagasitic Gulf, no material from sea floor is available. Only the distal environment has remained for investigation.

In fact, along the embankments and under the young Quaternary surface fracturing, brecciation, cataclastic and brittle deformation is present in different lithologies along the shores (locations in **Fig. 8**). A large variety of breccia occur, in most cases monomict breccia, clast and matrix supported with clasts from millimeter to decimeter size. However, typical impact melt breccia (matrix-melt breccia) and suevite (breccia with glass, crystal and lithic fragments), as well as distal ejecta layers containing spherules have not been recognized.The different types of breccia are shown in **Fig. 9**.

Fig. 9 Selected locations of fractionated and brecciated surface along the cost of the Pagasitic Gulf: **a)** Fractured gneiss quarry below hill of Amphanae with heavily broken surface; **b)**between Kritharia and Stavros distorted and brecciated crystalline limestones and schists, partly filled with reddish Pleistocene red beds and hydrothermal deposits, dipping towards sea;
c) Roadcut along Cape Ghoritsa showing different types of fracturing the Triassic marbles from simple fracturing to cataclastic monomict breccia and in part pulverization; **d**) Cape Ghoritsa, the surface exhibits consistently fine to moderate monomict brecciation and showing an open conjugate network of straight fractures; **e)** Intensive fracturing in small quarry below the village of Servanates (above Kato Lechonia); **f)** South of Paou beach (southwest of Arghalasti).

The coastal outcrops of monomict breccia are representative for many of their kind along the western shores between the villages of Afissos and Milina. They are most significant in platy crystalline limestones. The surface layers are chaotically brecciated and cut by irregular breccia channels cemented with matrix calcite and oxides; **g)** coastal outcrops at Milina, the breccia is topping broken layers of platy limestone; **h)** roadcut west of Panaghia chapel (Trikeri Bay) with a unique deformational geomorphological feature. The brecciated Quaternary surface seems to fill highly deformed depression in pulverized Triassic marbles. Photos V. Dietrich.

The outcrops along the northwestern coast between Nea Anchialos, Cape Agistri and the hill of Amphanae (Gulf of Volos) and in the main road cuts expose schists, gneisses and crystalline limestones, which are cut by numerous faults and fractures (**Fig. 8**). In general, all lithologies dip towards the gulf (**Fig. 9b**). Slumping appears using the 3D observation in the Google Earth maps. Most of the deformation, gentle folding and schistosity can be assigned to pre-Quaternary orogenic processes. Post-deformational features are steep normal down faulting parallel to the coastline (Anchialos Fault Zone) as well as minor perpendicular fault systems. The gneisses are deeply fractured in several areas (e.g. in the quarry below the hill of Amphanae, (**Fig. 9a**), the surface in addition chattered. Between Kritharia and Stavros crystalline limestones and schists are distorted and brecciated, partly filled with reddish Pleistocene red beds and hydrothermal deposits, dipping towards sea.

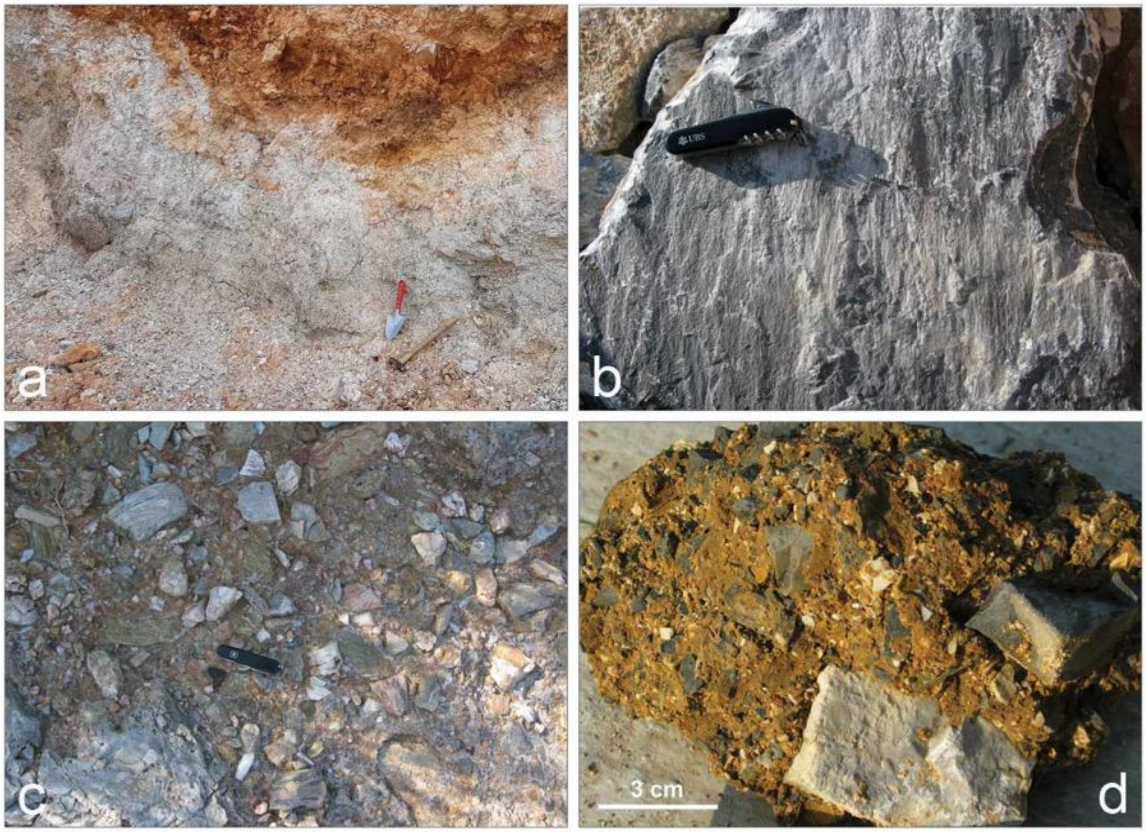


Fig. 10 Special deformation and brecciation characteristics; **a)** highly deformed depression in pulverized Triassic marbles filled by brecciated Quaternary surface. This effect cannot be explained by any recent dynamite blasting, due to the undisturbed dense vegetation above. The only interpretation remains at the moment due to an impact affect; **b)** weathered surfaces of crystalline platy limestones with narrow divergent ridges (striation) Old Trikeri Island and close to the port; **c)** polymict matrix supported breccia at Lefokastro; **d)** close up polymict matrix supported breccia with components of dark crystalline limestone and white marble (Servates above Lechonia). Photos V. Dietrich

A similar situation of intense fracturing is evident along the shore of Cape Ghoritsa for almost two kilometers between Volos and the cement factory of Asteria/Agria (**Figs. 9 c and d**). Outcrops are best exposed in the cliffs and in the main road cut. The coastal cliffs demonstrate that fracturing and brecciation in the middle Triassic to Jurassic marbles is a natural phenomenon and not the result of blasting. The construction of the new ring road of Volos and Agria opened over a distance of two kilometers perfect outcrops through the Triassic-Jurassic marble formation. Almost over the entire distance the marbles are fragmented, ragged and chattered. Monomict breccia are predominant, in the upper part meter-size blocks frequently are present. Further brecciation is present within the marble formation along the new roads from Agria to the village Drakia, from Kato Lechonia to the villages of Servanates (**Fig. 9e**) and Aghios Lavrendios, and from Ano Lechonia to Aghios Vlassios. In all cases, especially the surface of the marbles is highly fractured and exhibit strong striation. These features are repeated at the coastal cliffs of Rivera beach west of Kato Ghadzea. There, the monomict breccias are filled with reddish Pleistocene red beds and hydrothermal deposits, dipping towards sea.

The gently undulating peneplain morphology with altitudes between 300 and 400m of south-central part of the Pelion Mountain chain differs significantly from that of the mountainous, up to 1500m high northwestern part, cut by steep valleys, probably due to strong differential tectonic uplift during Tertiary times. The southern part is made up of thrust sheets of uncertain Triassic to Jurassic age, which is composed of epidote-actinolite-chlorite schists, mica schists, phyllites, crystalline limestones and platy marbles, as well as major metamorphosed mafic bodies and small lenses of highly tectonized serpentinites. The Quaternary surface is characterized by non-orientated deformation and chaotic brecciation by shearing and late faulting overprinting early thrusting during orogenic phases and uplift.

Similar aspects occur in the same tectonic units along the gulf coast between Afissos and Milina. Characteristic monomict and less polymict breccia are present north and south of Lefokastro and Paou beach (**Figs. 9f and g, 10c and d**). The surface layers of crystalline limestones are often chaotically brecciated√and cut by irregular breccia channels cemented with matrix calcite and oxides. In contrast, schists are and gneissic layers are only fractured; serpentinite lenses are not affected.

Cataclastic fragmentation and brecciation are characteristic features below the present surface in the Triassic to Jurassic marble formation in the Tiseo Mountains. The new road cuts along the gulf coast between Milina and Trikeri bay show some impressive examples (**Figs. 9h and 10a**). Matrix supported monomict breccias are abundant between Marathias bay and Avra. A few hundred meters west of the chapel Panaghia a local trough in the mountain side wall next to the road leads to an impression of a local impact phenomenon, since the white marble layers are highly compressed and pulverized, the trough itself filled with brecciated red bed material.

The style of fragmentation and brecciation changes due to the lithologies of the opposite mountains of Stefanania and Dhiasela in the Trikeri Peninsula. There, the white marble formation of the Tiseo Mountains is overthrusted by a complex zone of thrust sheets consisting of cherts, shales, schists, crystalline limestones and ophiolitic relicts, which turns into a thick sequence of Upper Cetaceous platy marbles and cherts. In many places along the road cuts up to the Trikeri Village, the wide overthrust zone is extremely fractioned and chattered including all grain sizes and large blocks in a loose unconsolidated sandy matrix, covered by very thin layers of soil, bushes and trees.

These morphological features of cataclastic fragmentation and brecciation continue to an extreme in the island of Palea Trikeri and in the islets of Strongyli, Psathi and Pithou, the latter investigated from the sea. The upper few meters below the soil and vegetation seem to be shattered with fragmentation down to centimeter dimensions. All lithologies are dipping towards the center of the gulf.

Surficial striation is generally known as long scratches and gouges on polished rock surfaces by glacial abrasion. However, on fresh surfaces and major broken blocks they turn out to be an erosional surficial effect of an internal striation (**Fig. 10b**). Penetrative straight and curved, closed or wide spaced surficial striations in metamorphic rocks are mainly a result of intersections of sets of healed planar fractures, in the case of metamorphic and tectonized limestones and marbles dislocations of twin-lamellae.

2.4 Tectonic and Planer Deformation in Quartz and Calcite

Sampling was concentrated on quartz veins in all lithologies along the shores and hill sites around the Pagasitic Gulf, thus in the distal environment of the possible crater formed by an impact blast. The goal was to detect impact related shock metamorphic deformation. In order to discriminate post-orogenic shock-induced cataclastic fabrics, orogenic tectonic fabrics had to be recognized and extracted. In most cases, multi deformational phases are present overprinting each other, which obliterates a proper identification.

Undulate extinction and "Boehm lamellae" (metamorphic deformation lamellae, MDLs) in quartz-fabrics as a progression of unorganized dislocations are the most common deformational fabrics and are regarded as results of tectonic deformation in the crust during orogenic processes (Böhm 1883; Christie and Raleigh 1959; Christie and Ardell 1974). Examples of metamorphic fabrics in quartz-rich schists, gneisses and veins are shown in **Figs. 11a and b**.

In contrast, *planar deformation fractures (PDF's) in quartz and feldspars* with a general thickness <1 µm and amorphous composition of the host mineral are the most diagnostic shock-indicators for high-pressures starting at 10-15 GPa. They are also recognized in other silicate minerals such as olivine and zircon. According to shock-experiments, PDF's transform into diaplectic glass at 35 GPa. The speed of the shock event inhibits the timing for solid-state transformation of quartz and feldspars to their high-pressure polymorphs stishovite and lingunite (French and Short 1968; Stöffler and Langenhorst 1994; Langenhorst and Deutsch 1998, 2012; Langenhorst 2002; French and Koeberl 2010; Reimold and Jourdan 2012) The "decoration" is the result of the amorphous lamellae and precipitation of fluid bubbles (water). Clear sets of close spaced "planar deformation fractures "(PDFs) have not been found up to date.

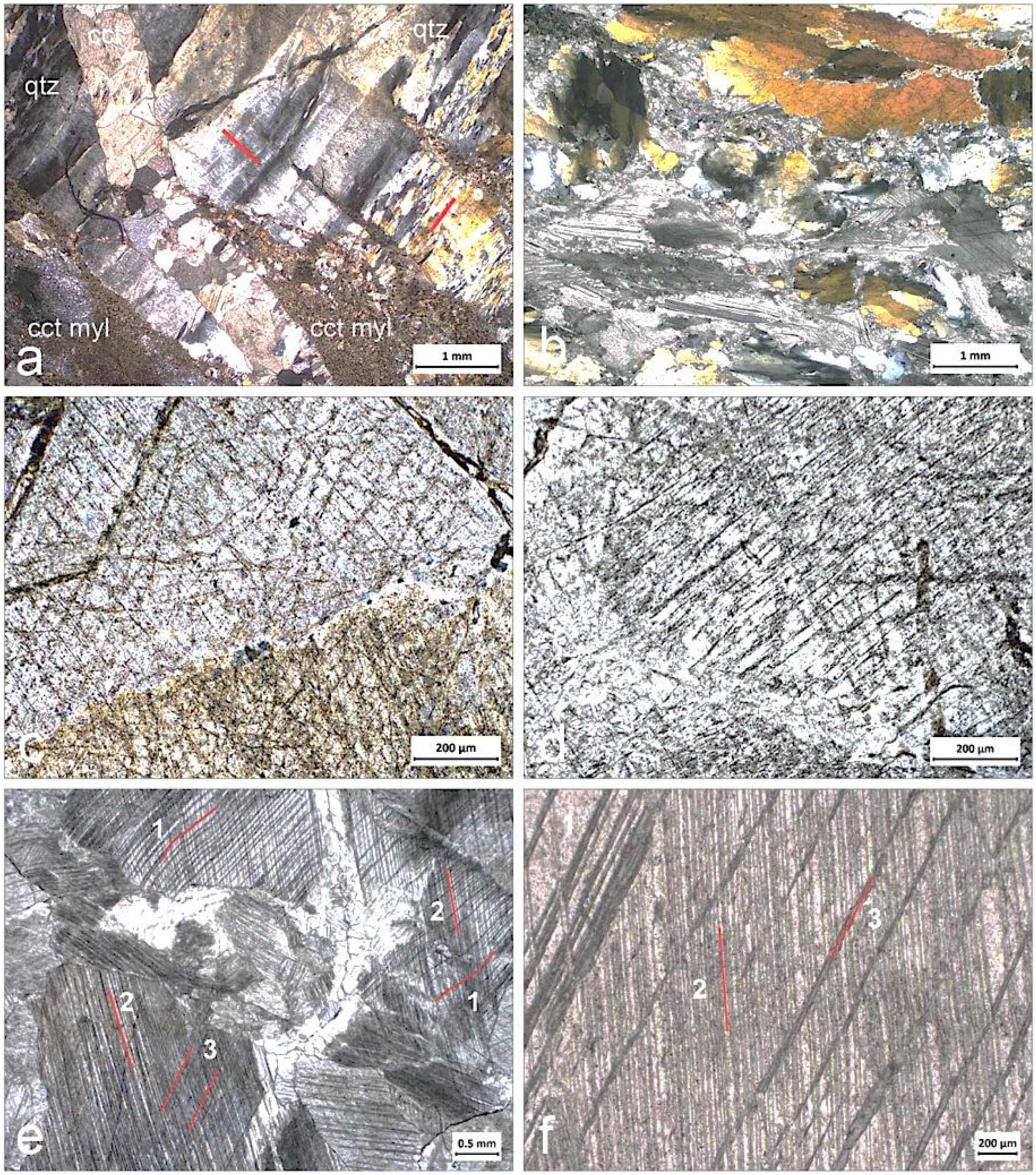


Fig. 11 Microphotographs of rock thin sections showing different styles of deformational characteristics in quartz and calcite;**a)** brecciated sample mylonitised crystalline limestone with highly deformed quartz components (indicated with red arrows) crosscut by a broken calcite vein; road north of Trikeri Village at Piridhistra; **b)**highly deformed multiple twinned calcite elongation and quartz (yellow colors) in brecciated marble from beach cliffs Rivera; **c and d)** quartz-fabrics with straight close spaced planar fractures with approx. 1mm thickness in different quartz grains in same sample at coastal rod east of Nea Anchialos; **e)**highly deformed marble with multiple sets of close spaced lamellae and fractures with red markers: 1) slight bend lamellae, 2) very closed spaced parallel fractures <1 □ m and spaces between 1-5 □ m; 3) wide spaced straight parallel planar fractures (construction highway above Asteria/Agria); **f**) twinned calcite crystals: 1) cut by sharp planar fractures, 2) close and wide spaced fracture planes with a thickness between 5-20 □ m, 3) wide spaced fracture planes (with red marker); road cut at monastery Paou. **e)** image under plane polarized light, all other images under crossed polarized light.

Subplanar and subparallel deformation lamellae, as well as weak "planar fractures (PFs)" with approx. 1 m thickness have been detected in some quartz crystals (**Figs. 11c and d**), which are interpreted as a result of pressure shock-induced metamorphic effects. In addition, cases of planer fractures decorated with tiny unidentified inclusions may represent the effects of contemporaneous fluid circulation. Similar PFs have been described from several meteorite craters.

Apparently, *calcite deformational effects* can easily be produced in target limestones by impact shock-induced pressures (Baratoux and Melosh 2003; Burt et al. 2005 in the Arizona Barringer crater). Multiple twinning in calcite is a common feature and originates from metamorphic deformation and recrystallization of limestones to marbles at low pressures and temperatures. It also occurs in coarse calcite crystals as products of hydrothermal or metasomatic fluids in the upper crust and near surface horizons, respectively. In addition, calcite shows a predominant cleavage usually in three directions parallel to the rhombohedron. Calcite cleavages as well as multiple twins are easily deformed by dynamic tectonic processes, such as by shearing and folding in faults, thrusts and folds (**Fig. 11b**).

Therefore, low- and medium-density twins in calcite formed by shock metamorphism, cannot be reliable distinguished from those formed by tectonic deformation; only high-density twins and planar fractures (PFs) that offset cleavage planes, may be regarded as impact related-shock effects (Langenhorst et al. 2000; Burt et al. 2005; Huson et al. 2009 and 2011; Hamers and Drury 2011). Consequently, these deformational effects can be recognized in the XRD powder pattern of calcite and dolomite in "Single Peak Profiling - Full Width Half Maximum" widening (Huson et al. 2009 and 2011).

Planar fractures (PFs) have been found in several cases in the crystalline limestones of low metamorphic grade as well as in the marble of the Triassic-Jurassic formation (**Figs. 11e and f**). The very closed spaced parallel fractures have a thickness <1 m and spaces between them of 1-5 m, whereas wide spaced straight parallel planar fractures are 5-20 m thick.These cataclastic, post-Alpine calcite deformation fabrics are compatible to the observed planar fractures in quartz grains and thus, indicative for an impact-induced event.

3 12,800 BP the Year of the Cosmic Body Impact

3.1 The Impact Hypothesis

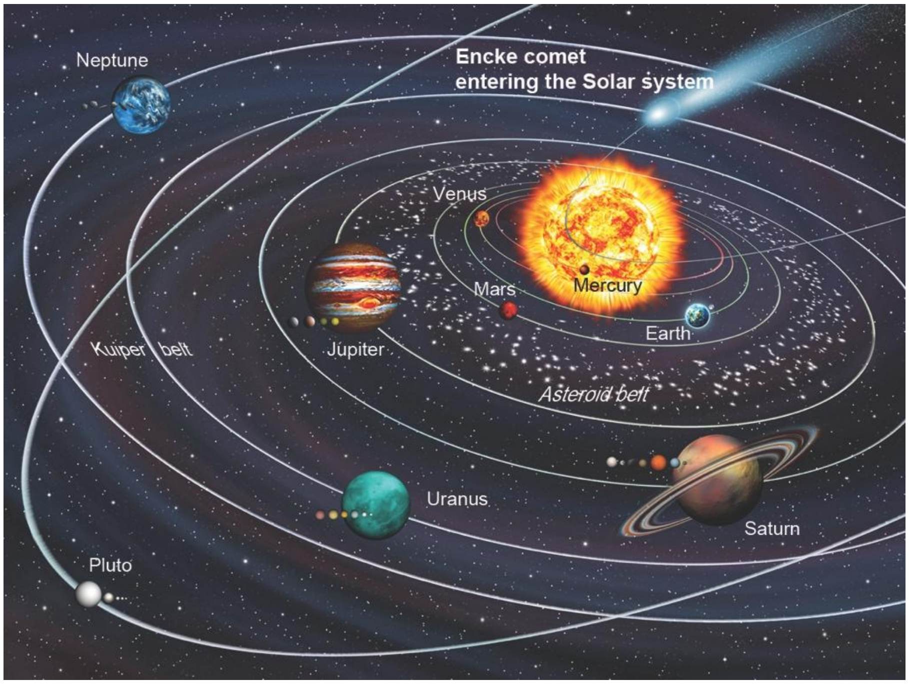
In the conventional way, the Pagasitic Gulf may be explained as a simple Pleistocene and Holocene tectonic depression, an extension of the AlmyrosBasin and intersecting the NW-SE Pelion Fault System as result of continuous uplift of the Olympus-Ossa-Pelion mountain range since Early Miocene time. However, a subsidence of the gulf can be ruled out because of the lack of shallow terraces. The Quaternary morphotectonic configuration of its mountainous surroundings with their lithologies dipping towards the gulf and style of brittle and cataclastic deformation in the surficial rock formations require a new approach of geological and geophysical interpretation. Within the framework of the above concept, the possibility of the impact hypothesis is analytically introduced in the following, where among other issues, the modelling of the existent geophysical data seems to be consistent to an impact case scenario.

3.1.1. Asteroid Impact or Comet Airburst

The irregular circular embayed shape of the coast lines as well as the size and the bowl-type bathymetry of the Pagasitic Gulf suggest for their formation an assumption of a complex crater structure as a result of an extraterrestrial impact event. All newly observed uncommon structural criteria (slumping, landslides) and special deformational phenomena (brecciation and planar microfractures) favor an origin of a blast pressure pattern as result of a possible impact of a cosmic body asteroid/meteorite impact or comet airburst.

Two types of meteoroids are recognized impacting the Earth's atmosphere (Ceplecha et al. 1998; William and Murad 2002).The first one consists of sublimating comets as they orbit the sun and are responsible for periodicmeteor showers. The second type of meteoroids, which vary in sizes from grains to kilometer large asteroids and composition, and which cross Earth's orbit intermittently, originates from theasteroid belt (**Fig. 12**), beyond Mars and share theorbital plane with the planetary bodies in the solar system. While asteroids are composed of metals and rocks, comets consist of ice, dust, rocky material, gas and organic compounds, both being relict material from the creation of the Solar system 4.5 billion years ago.

Fig. 12 Heliocentric orbit model. The solar system with its nine planets, the asteroid belt between Mars and Jupiter, the outer asteroid Kuiper belt and the unstable orbiting Encke comet coming close to Earth every 33 years. Modified image, courtesy of Adobe Stock.



Meteoroids as well as large asteroids entering the Earth's atmosphere collide at hypervelocity with atmospheric constituents resulting in mass (metals) loss by sputtering, evaporation, ablation and fragmentation (discussion in Rogers et al. 2005; Sukura 2013; Mathews et al. 2017). The luminous phenomenon that occur between 60 and 120 km resulting from collisional de-excitation of the ablated meteoroid atoms and excited atmospheric molecules are defined as meteors or shooting stars. Are meteoroids large enough and do not burn up in the atmosphere, they reach the ground as meteorites.

Normally, iron meteorites reaching the Earth's surface as compact bodies with hypervelocity, generate almost circular impact craters with walls of ejecta, and in case of large craters exceeding hundreds of meters in diameter a central uplifted dome of basement (Earth impact data base; review in Kenkmann et al. 2014). In contrast, stone meteorites and especially comets tend to break apart while entering the atmosphere and generating an air burst and pressure waves while moving down. Many small craters remain as witness of numerous impacts in a strewn field of meteorites over a large distance on the Earth's surface. The most recent and well-documented fall of a stone meteorite happened on February 15, 2013 causing a lot of local damages in the city of Chelyabinsk (Chelyabinsk 2013; Righter et al. 2015).

3.1.2 Impact Modeling

In order to test the observed structural criteria of the lithologies surrounding the Pagasitic Gulf: slumping, landslides and brecciation as well as the low-pressure impact fabrics in the limestones and siliceous rocks, we used the "Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth" (Collins et al. 2005). The results should give a first approximation about the impact crater size and depth, a possible discrimination about the character of the impactor, either an iron or stone meteorite or a porous ice comet as well as about the nature of impact as a single simple event or a complex airburst.

Basic input requirements are the impactor diameter, impactor density, impact velocity before atmospheric entry, impact angle, the distance from the impact at which the environmental effects are to be calculated, and the target type (sedimentary rock, crystalline rock, or a water layer above rock). Three general impactor types were chosen for modeling: an iron asteroid with the general density of 7500kg/m^3, a stone meteoroid with the general density of 3000kg/cm^3 and a porous dust and ice comet with a general density of 1500kg/m^3.

Typical impact velocities are 17 km/s for asteroids and 51 km/s for comets. The most probable angle of impact, which from a plane tangent to the impact surface, is 45 degrees. The generally observed distance of entry the Earth outer stratosphere is 100km.

As a consequence, the following results are outlined implementing the above impact program (Collins et al. 2005):

An ***iron asteroid*** of approx. 500m diameter begins to breakup at an altitude of 17500 meters, striking the surface at velocity 16.9 km/swith an impact energy is 7.02 x 10^{19} Joules = 1.68 x 10^{4}MegaTons TNT. The broken iron meteorite fragments strike the ground in an ellipse of dimension 0.788 km by 0.557 km and create a complex transient crater with a diameter of 8.34km with a transient depth of 2.95km, which turn into a final crater of 11km with 610m depth. Thecrater shape is normal in spite of atmospheric crushing; fragments are not significantly dispersed. The volume of the target melted or vaporized is 0.442 km^3. Roughly half the melt remains in the crater, where its average thickness is 8.08 meters.

The environmental effects are catastrophic on a regional scale: The seismic shaking reaches a magnitude M=8 on the Richter scale, the air blast a peak overpressure of 42 MPa blowing down all trees over more than 100km distance with half of supersonic speed. A large amount of target ejecta vaporizes or melts.

Such a scenario does not match at all the observed size of the Pagasitic Gulf and structural criteria along the shores and hill sites. Neither high-pressure impact derived typical shatter cones nor planar deformation features at microscopic scale are present. A possible impact of a smaller iron meteorite could not have produced by far large the size and shallow depth of the Gulf as well as the existing gravity anomaly.

In contrast, a ***stone asteroid*** with a max. dimension 1 km begins already to breakup at an altitude of 54000 meters, striking the surface at velocity 16.9 km/swith an impact energy is 2.24 x 10^{20} Joules = 5.35 x 10^{4} MegaTons TNT. The broken projectile fragments strike the ground in an ellipse of dimension 0.788 km by 0.557 km and create a complex transient crater with a diameter of 8.34km with a transient depth of 2.95km, which turn into a final crater of 11km with 610m depth. The volume of the target melted or vaporized is 1.14 km^3. Roughly half the melt remains in the crater, where its average thickness is 16.1 meters.

The environmental effects of large stone meteorite impact are also catastrophic, even on a lager regional scale than the impact of a half-sized iron meteorite. The seismic shaking reaches a magnitude of M=7.8 on the Richter scale, the air blast a peak overpressure of 89.5 MPa blowing down all trees over more than 100km distance with half of supersonic speed. A very large amount of target ejecta vaporizes or melts. The scenario of fragments of a very large stone meteorite does not match at all the observed size of the Pagasitic Gulf and structural criteria along the shores and hill sites. The high-pressure and temperature impact effects exceed by far all existing deformational features around the Gulf.

A more realistic cosmic impact scenario that could fit all observed ground parameters of the Pagasitic Gulf and its surroundings evolves from the model calculation using a ***porous dust and ice comet*** of 1km dimension with a density of 1500kg/m^3 and an atmospheric impact velocity of 50km/s. The breakup of such a projectile starts already at 89.7 km with a very high impact energy of 9.52 x 10^{20} Joules = 2.28 x 10^{5} Mega Tons TNT. Due to its fragile constitution, the large dust and ice comet should fragmentate within seconds as multiple airbursts instead of reaching the ground. However, the very high impact energy could create a complex transient crater with a diameter of 13.47km with a transient depth of 4.74km, which turn into a final crater of 18.9km with 717m depth. The model calculation of both, size and depth of the crater can only be first approximations, since the model deals with a real impact of the target by the projectile.

The environmental effects are catastrophic on a large regional scale: The seismic shaking reaches a magnitude of M=8.2 on the Richter scale, the hot air blast of the bursts a peak overpressure of 242 MPa blowing down all trees over more than 100km distance with half of supersonic speed and causing wild fires everywhere.

Despite such an environmental cataclysm, the airburst may have devastated a vast area by an air blast and thermal radiation but did not affect the crystalline underground and Neogene cover in terms high-pressure and temperature to cause evaporation and melting as well as impact deformational features. Considering the assumption of a multiple airburst starting at high-altitude, pressures emitted from the air blasts with a calculated peak overpressure of approx. 0.2 GPa could have over deepened the entire shallow Pleistocene basins Pagasitikos and Almyros, as well as the plains of southern Pelion, finally reaching the morphological impact-crater shape of the Pagasitic Gulf.

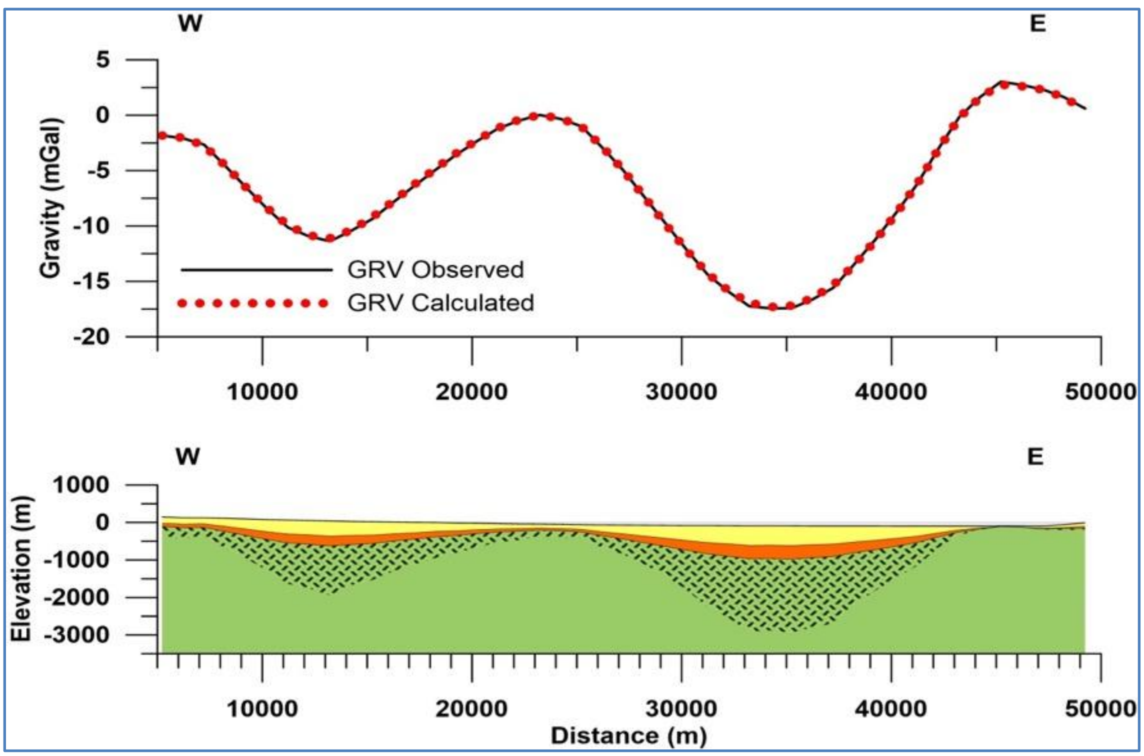
An attempt was made to investigate whether the observed gravity anomaly over the wider area of Pagasitic Gulf could account for such a model of the upper crust, considering the characteristics of the top upper layers being suffered by a case of an air-burst. The Gravity Anomaly Map of Greece (Lagios et al. 1995) was primarily considered and used in the present impact hypothesis for the broader area o Pagasitic Gulf. The gravity data of the enriched Gravity Data Bank of Greece (Lagios et al. 1996) were used and reduced to gravity anomaly values.

Such kind of model is presented along *Profile E-W* (**Fig. 13**) that was extended on both sides over the gulf. A borehole at the western part of the area on land was used as control of the sedimentary sequence in the above model. It appears that the outcome of the above model relating to the *final depth* (800m) and *diameter crater (20km)* dimensions is consistent with the results of the impact program outlined above (717 m and 18.9 km, respectively).

Fig. 13 A possible gravity model over an extended profile on both sides of Pagasitic Gulf. For the densities applied, see as in the text of *Supplementary Section*.

3.1.3 A Comet impact as airburst in the stratosphere, the Unique Tunguska Event

The Tunguska catastrophic blast 1908 in Siberia, which devastated an area of 2,150 km^2 knocking down some 80 million trees, is considered today by the majority of the scientific community as a result of a comet airburst (Kulik 1939; Longo et al. 1994, 2005; Longo 2007). However, after 80 years of research, the nature and composition of the comet still remains mysterious, although in recent years the evidence of a comet airburst became more valuable, since traces of association of high-pressure carbon allotropes, diamond and lonsdaleite together with troilite, taenite, γ-Fe and schreibersite have been found in peat close to the Tunguska blast epicenter (Zlobin 2013; Kvasnytsya et al. 2013).



A possible Tunguska impact scenario has been intensively discussed in Longo (2007). The most feasible explanation is to assume an extremely bright comet (bolide), "Tunguska Cosmic Body" entering the Earth's atmosphere with 10-20km/s. Boslough and Crawford (1997).

Proposed a model of a "plume-forming" atmospheric explosion, divided into three steps: an entry phase with melting and vaporization of the bolide's surface material, simultaneously with a fireball phase shooting energy and dust as large plume many hundreds of kilometers upward and followed by its back splash onto the upper atmosphere, releasing additional energy as its collapse and impact at an "epicenter", the area of major devastation. This and later plume-forming models couldreasonably confirm the eye-witness observations, the vast forest devastation," bright nights", observed over the northern hemisphere from England to eastern Siberia, a major earthquake and the barometric and magnetic field disturbances.

The air-burst models were compared to destruction of nuclear weapons, with approx. 10-15 megatons of TNT, a possible height and trajectory of the burst in order to receive a first estimate of the energy involved in such a catastrophic explosion. The later "Foschini Hypersonic Flow" model (Foschini 1999 and 2001) takes especially the fragmentation of a small bolide during the bow shock of the entry phase into consideration, the changes of the hypersonic flow coupled with an increase of deceleration and efficiency of the airburst. The assumption that a bolide disrupts and vaporizes while entering the stratosphere at approx. 20km height and releasing energy during four major bursts on its way down with a maximum burst between 6-8km, has been qualitatively demonstrated in the "Anfinogenov Spindle" Anfinogenov (1966) and Anfinogenov and Budaeva (1998). Longo et al. (2005) concluded on the basis of reinvestigation of the geometry of the devastated surface showing a butterfly-shaped blast patterns (**Fig. 14)** and the eyewitness reports that the bolide might have emitted different energy from explosions of multiple bodies.

3.1.4 Application of the Tunguska Event to the Genesis of the Pagasitic Gulf

Despite the fact that the Tunguska event is the only one on Earth in recent times and not yet fully understood, the attraction is great to search for areas, which have similar enigmatic characteristics that cannot explained by simple conventional geological and morphological phenomena. This is definitely the case for the Pagasitic Gulf. For the reason thebutterfly-shaped blast patterns of the Tunguska event (Longo et al. 2005) is shown as overlay onto the Pagasitic Gulf (**Fig. 14**). It demonstrates at least similar dimensional aspects between the Tunguska devastation and the gulf and permits the reasonable assumption of differential emission of energy due to multiple bursts of several bodies.

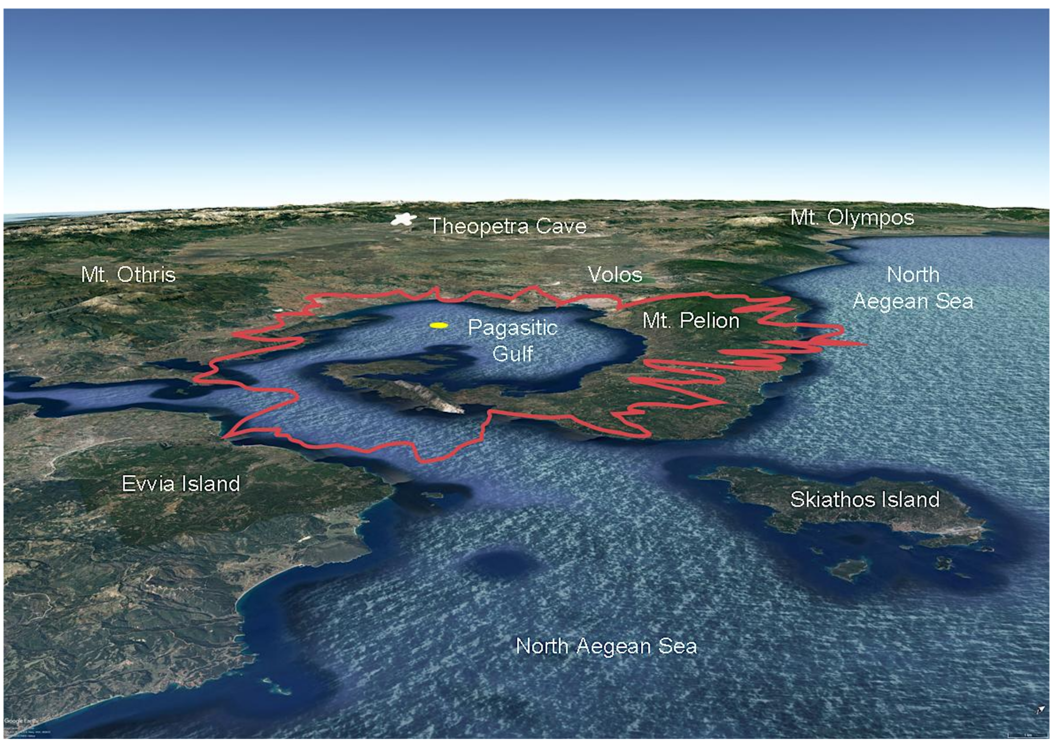


Fig. 14 Overlay ofthebutterfly-shaped blast patterns (outlined in red) of the Tunguska event (Longo et al. 2005) with the maximum of tree fall devastation (yellow spot as inferred "epicenter"), for comparison with a similar possible scenario in the area of the Pagasitic Gulf. Image: Digital Globe Google Earth.

Besides all structural criteria from megascopic to microscopic aspects, discussed in the previous chapters, further investigation has to follow to establish the proof of an air burst combined with an impact of cosmic bodies, e.g. a search for spherules, high-pressure carbon allotropes and minerals.In contrast to the Tunguska area the Pagasitic Gulf represents an irregular circular depression with a present-day max depth of approx. 100 m.

4 Hellas and the World on Fire and Flood

4.1 Fires All Over, Pagasitic Gulf Airburst Model

Structural and sedimentological criteria in the region of the Pagasitic Gulf point to a major rapid change of the environment in central Greece between Late Pleistocene and Early Holocene and may coincide with the climate change at the onset of the Younger Dryas in the northern hemisphere at around 12,800 ± 150 years ago (Kinzie et al. 2014). We are tempted to relate the dramatic environmental cataclysm with the hypothesis of a collision of a large comet or asteroidof the inner solar system with the Earth disintegrating over the northern hemisphere at around 12,800 B.P., and consequently leading to countless airbursts and impacts with a wide spread of wildfires and biomass burning, consuming about 10 million km² or about 9% of the Earth's terrestrial biomass(Wolbach et al. (2018 a and b).Such an atmospheric entry may have started over North America and the Laurentide Ice Shield, reaching also Fennoscandia and northern Europe.

The irregular circular embayed shape of the coast lines, as well as the bowl-type bathymetry of the Pagasitic Gulf, suggest for their formation an interpretation of a major airburst creating a giga air blast that started entering the atmosphere already at high altitude, similar but on a mega-scale compared to the inferred situation of the Tunguska event (Shuvalov and Trubetskaya 2007), rather than an impact of a solid meteorite of large dimension, as it is also indicated by the geophysical modelling..

The hypothetical cosmic impact scenario that could fit all observed ground parameters of the Pagasitic Gulf and its surroundings evolves from the model calculation using a *porous dust and ice comet* of 1km dimension with a density of 1500kg/m³, an atmospheric impact velocity of 50km/s and entrance angle of 45 degrees. The breakup of such a projectile starts already at 89.7 km with a very high impact energy of 9.52 x 10^{20} Joules = 2.28 x 10^5 Mega Tons TNT. Due to its fragile constitution, the large dust and ice comet should fragmentate within seconds as multiple airbursts instead of reaching the ground. The latter could explain the irregular and slightly oblong shape of the gulf and the occurrence of several bays due to multiple small impact craters formed at the same time.However, the very high impact energy could create a main complex transient crater with a diameter of 13.47 km and transient depth of 4.74km, which turn into a final crater of 18.9 km with 717m depth (**Fig. 15**), consistent to the present-day gulf dimensions and geophysical modelling.

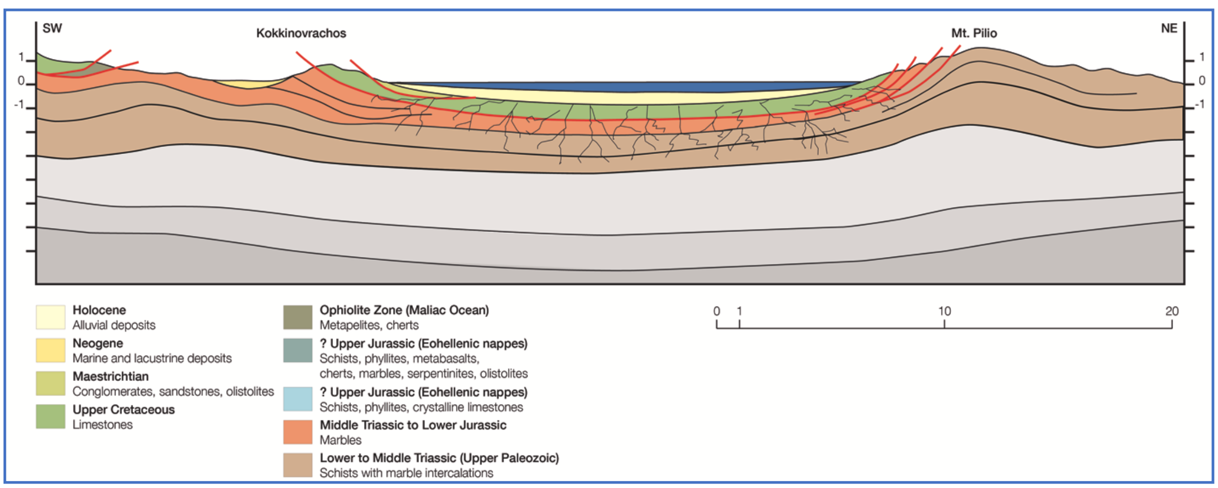


Fig. 15 The Pagasitic Gulf as result of the Pagasitikos Airburst Model. A general model of a complex airburst blast. The airburst and accompanied high-temperature air blast caused heavy fractionation and brecciation in the surficial rigid lithologies, as described in the previous chapters, but did not affect the crystalline underground in terms high-pressure impact deformation and temperatures to cause melting and evaporation. The effects of seismic shaking with a magnitude of M=8.2 led to collapse structures, slumping and landslides in the surrounding coastal mountains and over deepened the entire shallow Pleistocene basin.

The environmental effects according to such a giant airburst model are catastrophic on a large regional scale: The seismic shaking reaches a magnitude of 8.2 on the Richter scale, the hot air blast of the bursts produces a peak overpressure of 242 MPa, blowing down all trees over more than 100 km distance with half of supersonic speed and causing wild fires everywhere (**Fig. 16**). The airburst may not have devastated only a vast area by the air-blast and thermal radiation (modeling in Shuvalov et al. 2014), but also may have caused heavy fractionation and brecciation in the surficial rigid lithologies in the surroundings of the Pagasitic Gulf (e.g. the low-pressure impact fabrics in the limestones and siliceous rocks, as described in the previous chapters.

But did not affect the crystalline underground in terms high-pressure impact deformation and temperatures to cause melting and evaporation). The effects on the soft and permeable Neogene sediments can only be found and clarified by core-drilling into the central parts of the Pagasitic Gulf.

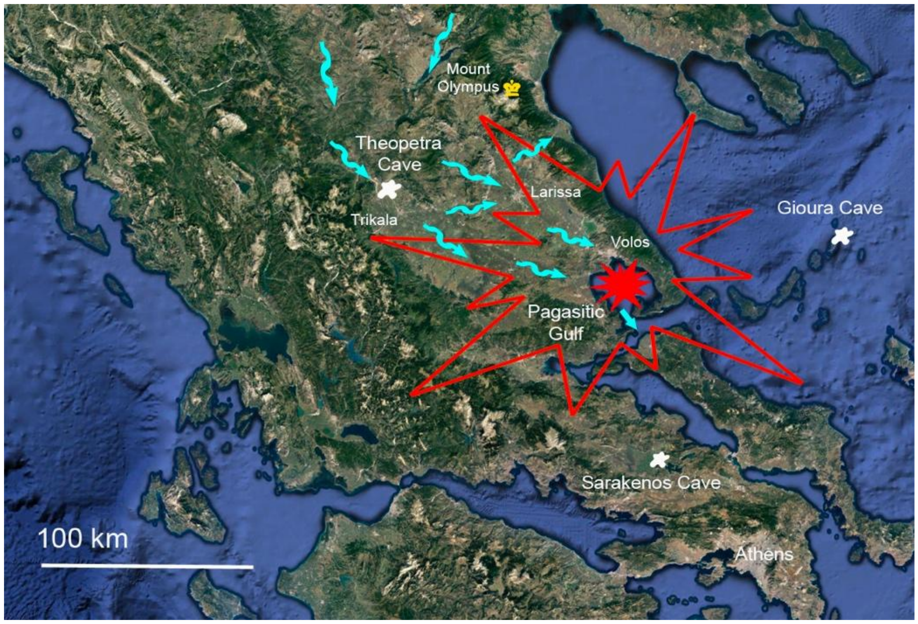


Fig. 16 demonstrates the possible extend of devastation of such a giant airburst covering parts of Greece and North Aegean Sea as well as flooding from north (blue arrows) at the rapid onset of the Younger Dryas. Image: Digital Globe Google Earth.

Considering the assumption of a multiple airburst starting at high-altitude, pressures emitted from the air blasts with a calculated peak overpressure of approx. 0.2 GPa could have over deepened the shallow Pleistocene Pagasitic basin reaching the morphological shape of the present gulf. The effects of seismic shaking with a magnitude M=8.2, and accompanied wave propagations with intensities of VII and VIII on the Mercalli scale, should have caused many collapse structures, slumping and landslides in the surrounding coastal mountains around the Pagasitic Gulf.

Remnants of catastrophic wildfires and flooding in the wider environment of Pagasitic Gulf are evident so far only in a few locations, i.e. in caves, acting as geological traps of the past. So far, the best location could be found in the Theopetra Cave on the northwestern end of the large Thessalian plain and in the Sarakenos Cave in central Boeotia, both caves ca. 100 km away from Pagasitic Charcoal infills yielded Carbon-14 ages between 12,000- and 13,000 years cal. BP, indicating the sharp onset of the cold Younger Dryas and a longer time gap to the Neolithic period.

Such a cataclysmic airburst scenario must have had a dramatic impact to the entire region (**Fig.16**) in central Greece. Surface pressure waves, lightning and thunderstorms deforested and burned a vast area with wild fires, extinguishing all terrestrial life. This must have affected almost the entire Pleistocene human population of hunters and gatherer, living in small fell tents, brushwood huts, and mammoth-bone dwellings. The assumption is based on the fact that a large fauna and human settlements must have existed in the plains and along the river banks and shores of the shallow lakes (flood plains) formed during the last warm Bølling-*Allerød* period between 14,700 and 12,800 years BP.

Dispersed Paleolithic pottery remains and artifacts have been reported from many other Paleolithic sites in the central Balkans, dispersed in fluviatile terraces and ploughed fields (Dogandžić et al. 2014; Cummings et al. 2014; Heffter 2014; Mihailović 2014; Reingruber 2017). It is possible that only small groups of cavemen survived the catastrophe, e.g. in the Gioura Cave in the North Aegean Sea (Sampson 2008b). Remnants of catastrophic wildfires and flooding in the wider environment of Pagasitic Gulf are evident so far only in a few locations, i.e. in caves, acting as geological traps of the past. So far, the best location could be found in the Theopetra Cave on the northwestern end of the large Thessalian plain, ca. 100km away from Pagasitic Gulf (**Figs.16**).

The charcoal infill between chaotic silt-rich upper Mesolithic sediments (**Figs. 17 and 18**) yielded an age gap occurred between around 13,000 cal. BP (DEM-249) and 11,200 cal. BP (DEM-142), recorded by Facorellis et al. (2001 and 2013) (**Fig. 19**).

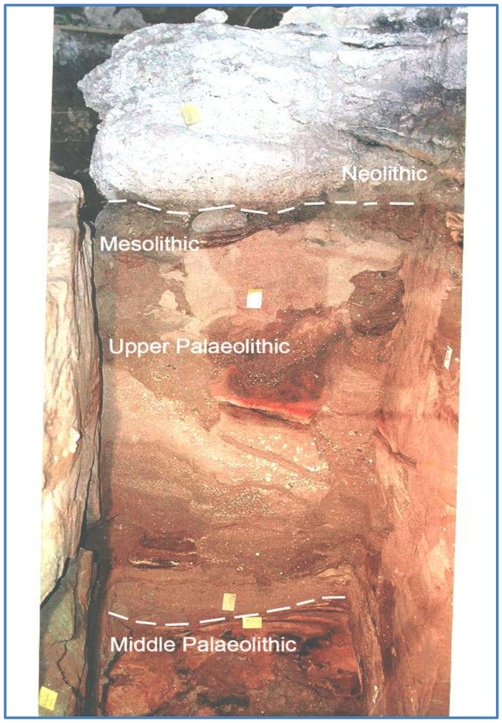


Fig. 17 Excavated trench showing the stratigraphic section between Middle Paleolithic and Neolithic periods (Kyparissi-Apostolika 2015). Note the chaotic Paleolithic sequence between reworked clay, silt, brecciated and black burnt layers, which are interpreted as effects of slumping and invasion of waters (Karkanas et al. 2000; Karkanas 2001).

Fig. 18 Excavated surface of lithological layer 2.11m with large charcoal and soot flakes, from where the samples DEM-249 yielded cal. ages BP: 13,130–12,910, 68.3%, 13,170–12,660, 95.4% (Facorellis et al. 2001).

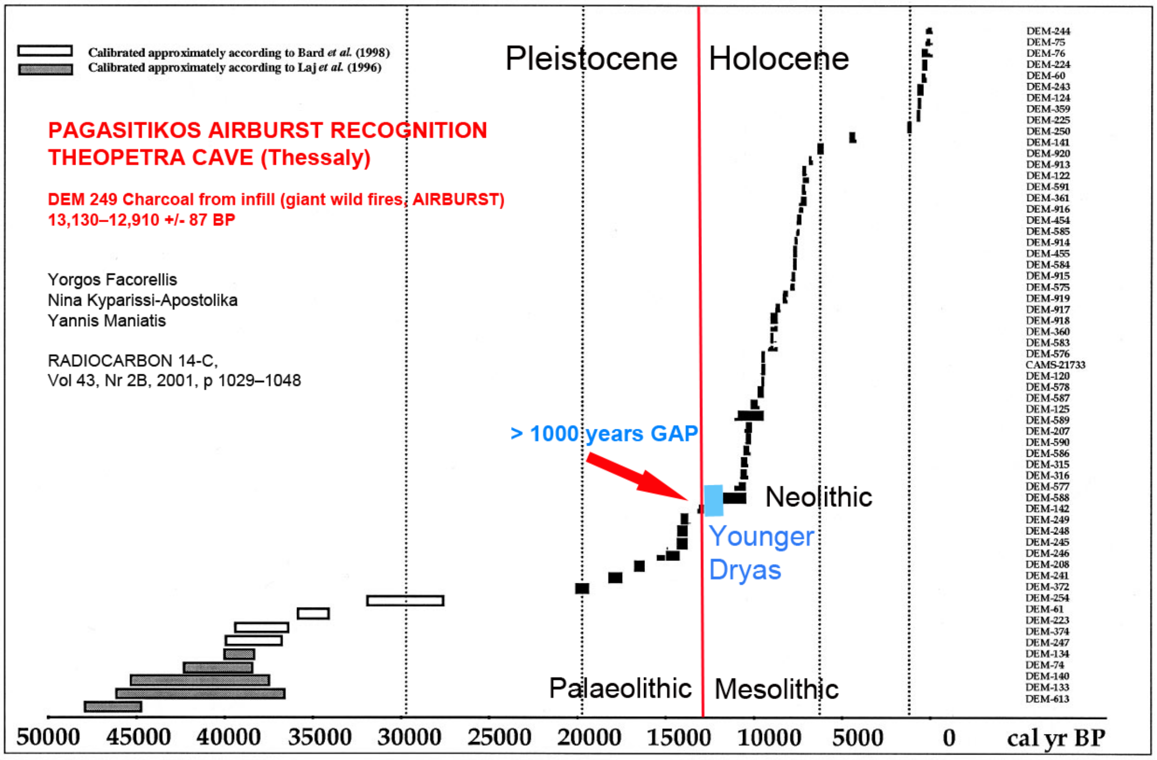


Fig. 19 The distribution of calibrated C-14 dates during the Upper Paleolithic and Neolithic until present from excavated lithologies in the Thessalian Theopetra Cave (Facorellis et al. 2001). Note the data of charcoal infill from the layer just below the overlain Neolithic lithologies (**Fig.17**), as well as the time gap of more than 1000 years during the cold Younger Dryas period.

The complex matter of sedimentation, indicating the existence of large fires and accompanied chaotic flooding could well be interpreted as the effect of the cataclysmic airburst and blast at Pagasitikos.The almost entire absence of bone residues in the Paleolithic embankments in all central area caves has been explained by a transformation of bone apatite into authigenic complex phosphate minerals, calcite and amorphous silicate by burning, water influx and diagenesis (Karkanas and Weiner 2000; Karkanas et al. 2000). The diagenetic formation of silt and clay, filled in through channels of invasive waters could have been a combination of the giant air-blast dust and subsequent strong flooding, probably linked to the drainage of the Baltic See and loose deposition due to the mega change of high-altitude winds from the west (Brauer et al. 2008) with the sharp onset of the Younger Dryas. The lowest part of the embankments in the Sarakenos Cave in Boeotia (Central Greece), about 100km south of the Pagasitic Gulf (Fig. 16), shows continuous carbon layers (Fig. 20), which could represent relict sedimentary ashes (soot) of large wildfires, most probably related to the proposed Pagasitikos airburst and blast towards south. The deepest carbon horizons fit with Pleistocene/Holocene boundary (Sampson 2008a; Sampson 2014), since small charcoal particles gave an age of 12,345+/-70 years cal. BP. A fine-grained sedimentary layer containing a "huge concentration of ash and burnings", but without any artifacts, yielded a long-time gap to overlying charcoal deposits derived from hearth and dated around 9,200 years cal. BP, a transitional age from Mesolithic to Neolithic periods. Thus, the similarities between catastrophic environmental impacts of the Pagasitic airburst in the two prominent caves, which were used for safety and refuge by Paleolithic hunters-gatherer, are obvious.

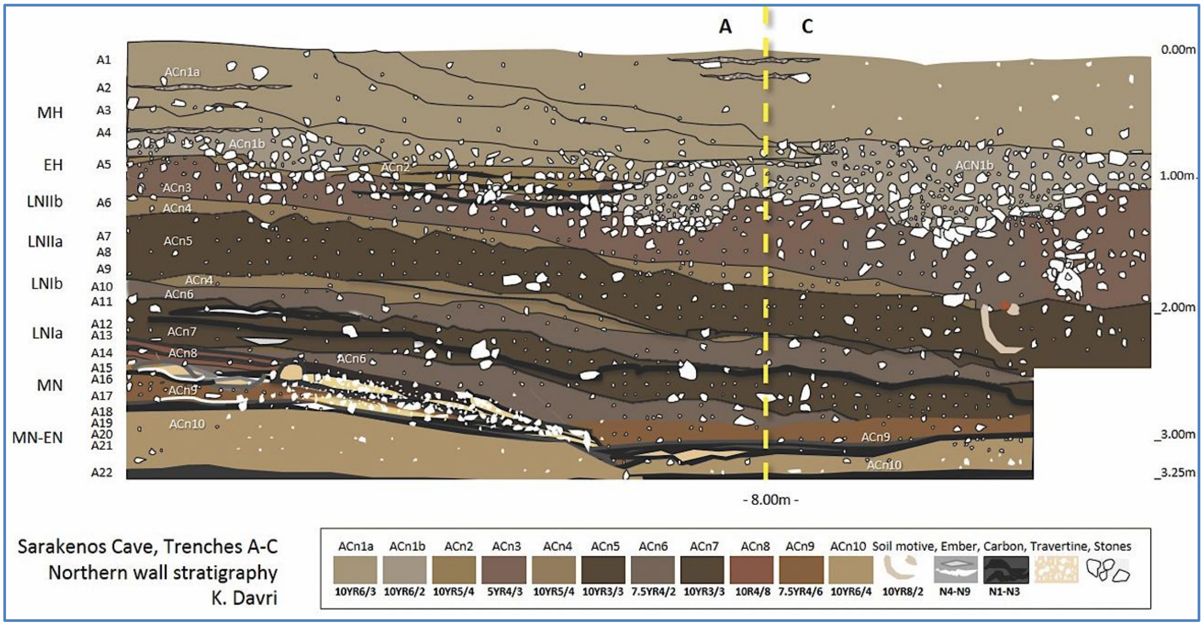


Fig. 20 Sarakenos Cave stratigraphy from uppermost Paleolithic MN-EN through Mesolithic and Neolithic times. Interesting to note the layers of carbon and lenses of ember at the deepest horizons at the Pleistocene/Holocene boundary (Sampson 2008c; Kaczanowska et al. 2016). Credit to Konstantina Davri

Similar black carbon rich marls were also detected at approx. 50m depth below freshwater clay in the Almyros Plain between the Zerelia Lakes and Almyros in a water exploration drill (Costas Kyriakopoulos, personal communication). The drill-hole penetrated 250m of intercalated clay, marls and gravel, indicating an interaction between rapid freshwater floodplain sedimentation and fluviatile gravels derived from the Orthris Mountains. Further investigations are necessary in order to date these carbon (? soot) deposits and search for possible airburst remains, such as spherules and nanodiamonds.

4.2 Cataclysmic flooding in the Northern Hemisphere

The distribution of the ice caps of the arctic polar region is shown in **Fig. 21**, which covered the entire area of North America, Alaska, Greenland and Iceland as well as northern Europe and part of Siberia. It is self-understood that the North Pole and most parts of the Arctic Ocean were also covered with ice of variable thickness.

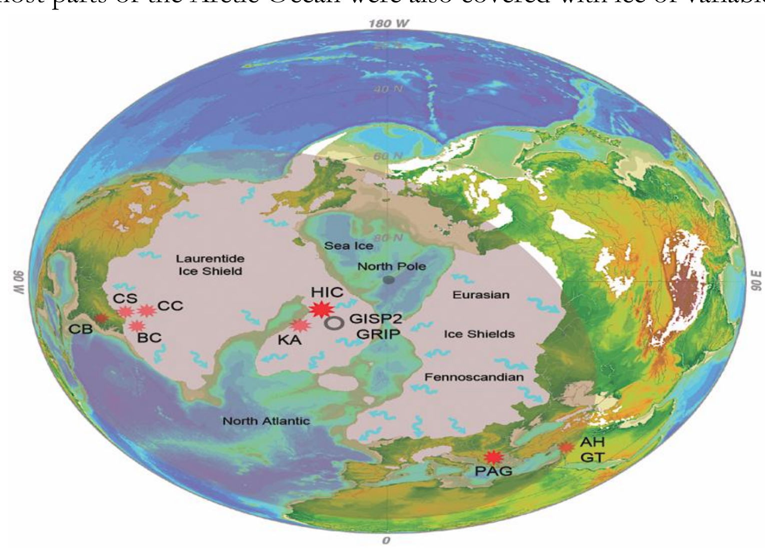


Fig. 21 The Laurentide Ice Shield and Eurasian/Fennoscandian Ice Shields at the Last Global Maximum (LGM, 24-18 ka cal. BP, Ehlers and Gibbard 2007), modified. Impact effects of cosmic bodies at 12,800 BP and the distribution of nanodiamonds(reddish-grey shaded area), and the directions of cataclysmic freshwater flooding (blue arrows).

Abbreviations: GISP2 & GRIP Greenland ice core dust of 12,896 ± 4 years BP, associated with a large Pt anomaly, which is interpreted as result of a large Ir-poor iron meteorite shower (Petaev et al. 2013; review in Rasmussen et al. 2014). Major possible impact/airburst localities: AH: *Abu Hureya / lake Assad, Syria*, Sweatman and Tsikritis 2017; BC: *Bloody Creek / Nova Scotia*, Spooner et al. 2009; CB: *Carolina bays along Atlantic coast between Delaware and northern Florida*, Zamora 2017; CC *Corossol crater / St. Lawrence Gulf Quebec*, Higgins et al. 2011; CS: *Charity Shoal / Lake Ontario,* Holcombe et al. 2001; GT: *Göbekli Tepe / southern Turkey*, Dietrich et al. 2013; PAG: *Pagasitic Gulf* this work; HIC: Hiawatha impact crater; Kjær et al. 2018

High-energy impact burst of cometsand meteorites of a giant cosmic shower could not only have triggered large wildfires and biomass burning but also have destabilized and melted parts of the Laurentide Ice Shield according to the controversial hypothesis of Firestone (2007) and flooded large parts of the North America, i.e. in the coulees and channeled Scabland Complex Washington, in the St. Croix River Minnesota and in the Finger Lakes of New York (Bretz 1925; Hunt 1977; Condron and Winsor 2012; Teller 2012). Very recently, a large impact crater has been found beneath the Hiawatha Glacier in northwest Greenland (Kjær et al. 2018). The age of the 31-kilometer-wide and up to 1000m deep crater has been estimated according heavily disturbed Pleistocene ice overlying Precambrian basement as well as to the continuous and conformable Holocene ice sheet cover as close to 13,000 years BP. The authors imply that such a large crater must have been formed by an impact of an approx. 1km iron asteroid.

If the Firestone hypothesis holds for the Laurentide Ice Shield it could also be applied to the ice caps of Fennoscandia and western Siberia, named the Eurasian Ice Sheet Complex (**Fig. 21**): EISC, Patton et al. 2017), which was the third largest ice mass during the Last Glacial Maximum (LGM).

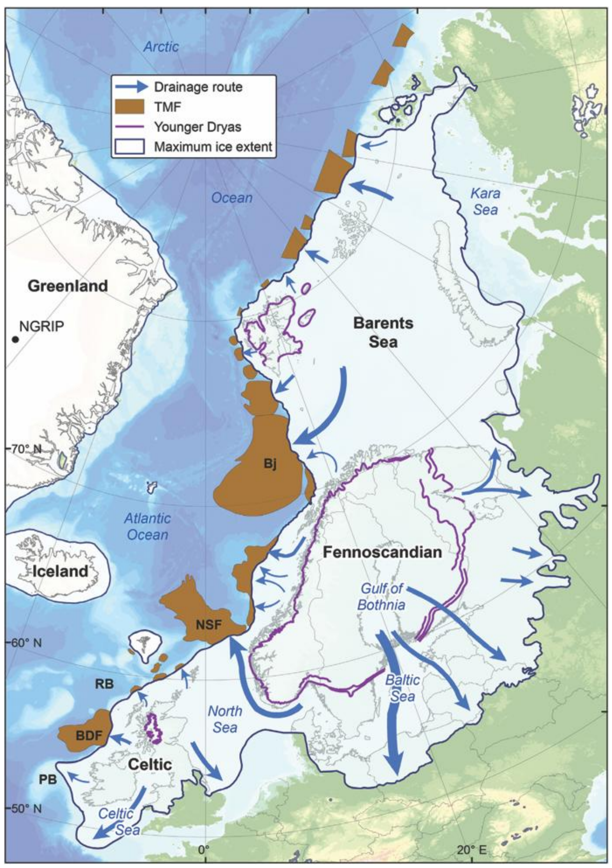


Fig. 22 Major drainage routes of the Eurasian ice sheet complex; credit to Patton et al. (2017) with adaption from Stokes and Clark (2001), Ottesen et al. (2005) and Clark et al. (2012). Locations of major trough mouth fans (brown) were adapted from Dahlgren et al. (2005) and Batchelor and Dowdeswell (2014). PB: *Porcupine Bank*; BDF: *Barra and Donegal Fans*; RB: *Rosemary Bank*; NSF: *North Sea Fan*; Bj: *Bjørnøyrenna Fan*. Glacial limits are compiled from Ehlers and Gibbard (2007), Patton et al. (2015) and Stroeven et al. (2016).

Recent evidence for the extension of the Celtic ice sheet onto *Porcupine Bank* (PB) (Peters et al., 2015) and into the southern *Celtic Sea* (Praeg et al., 2015) was also incorporated.

Recent studies revealed that two proglacial lakes of the Fennoscandia Ice cap (FIC), the Baltic Sea and the White Sea grew dramatically during Bølling/Allerød warm climate period. Thus, the European rivers, such as the Rhine, Elbe, Oder were heavily affected by the melting of the FIC. Between 14.9 to 12.9 ka BP the modeling results indicated a melting of the EISC on average 750 Gt per year, maximum rates >3000 Gt per year.

At around 12,800 years, an instant onset of strong flooding of freshwater from EISC and the voluminous proglacial lakes could have been triggered by a giant comet break-up and impact over the Laurentide and Eurasian ice shields (**Fig. 22**), leading to the cataclysmic floods towards southern Europe and Mesopotamia, mainly through pre-existing large rivers, which were not blocked by mountain ranges, e.g. River Po into the Adriatic, the Danube, Tyra and Dnepr into the Black Sea, and the river Volga into the Caspian Sea. Time markers, such as an increase of lacustrine and freshwater sedimentation coincide with a strong increase of freshwater at the Pleistocene Holocene boundary.

5 Conclusion

A challenging hypothesis of an impact origin of the Pagasitic Gulf in the region of "Hellas" (historical Greece) has been put forward and considered here on the basis of local geological, petrological, chemical, isotopic, oceanographic data, as well as on archaeological evidence of the broader area. This provocative suggestion was integrated within the framework of the cataclysmic cosmic shower in the northern hemisphere about 12,800 years BP and the sharp onset of the Younger Dryas. The resulted gigantic airburst on the ground surface being produced by an impacting 1km-ice-comet (or asteroid) on the Earth's atmosphere gives model estimates that are consisted with the present-day form of the Pagasitic Gulf, which is also consistent with the outcome of geophysical modelling of the associated residual gravity anomaly field (not though constituting a proof).

Concluding as a final remark, the present work has the ambition to trigger and stimulate a multi-disciplinary interest of the scientific community for further work and research in the broader area of the Pagasitic Gulf and provide more answers in the missing links already outlined above.

Acknowledgements:

We thank Jean Pierre Burg (emeritus professor ETH) and Efthimios Gartzos (emeritus professor Agricultural University of Athens) for fruitful discussions in the field; Viktor Sakkas and Stelios Chailas (Geophysics Dept., National and Kapodistrian University of Athens) for geophysical processing of the gravity data and preparation of the manuscript.

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