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THE EFFECTS OF EARTHQUAKES ON THE NATURAL ENVIRONMENT IN GREECE

Greece is one of the most tectonically active regions of Europe. If contemporary endogenous processes are indeed reflected in surface sculpture, their effects should be most clearly visible in Greece. Earthquakes are the most frequent and common examples of lithosphere mobility. That is why their sculpture-forming significance will be discussed as the most important morphogenetic instance of common tectonics.

Table 1 shows a set of strong quakes (magnitude ≥ 6) from 550 BC to 1986 AD, which were followed by registered changes in the earth's area structure, according to data in catalogues about Greece. The data preceding 18th century are clearly incomplete. It has, however, been taken into account, because they refer to probably the strongest quakes of their times, and may show general activity of the period.

In the examined duration of time, over 360 strong seismic quakes were registered in Greece. Only some of them (at least 125 according to Table 1) had an immediate and visible influence on the most external part of the lithosphere (naturally, without taking into account the damage incurred by human constructions).

It seems interesting that there is no clear connection between the quake strength and the concentration of the accompanying phenomena. Of 25 shallow and 13 deep earthquakes with a magnitude exceeding 7, only 14 and 6, respectively (56% and 46%) clearly gave way to what might be called changes in surface sculpture. This value becomes significant when compared to the one obtained for all earth quakes (irrespective of focus depth) of a magnitude of 6 or higher. In this respect, only 125 of 364 quakes (34%) had a morphogenetic effect.

The surface sculpture processes accompanying seismic phenomena had direct or indirect character, depending on whether they were connected solely with geophysical changes within the earth's crust, or whether they were the effect of these processes concurring with exogenous elements.

DIRECT SEISMIC SCULPTURE FORMATION PROCESSES

This data proves that seismicity was most often connected with the creation of surface cracks. This was registered in 59 out of 125 cases included in Table 1, and it was only in the 19th and 20th century that cracks exceeding 1 kilometre in length were registered 12 times (including 8 times in the 20th century). The longest one was registered in 1894, on the west coast of the North–Euboean Bay. In 10 out of these 12 breaks in the surface continuity, there were also vertical shifts, reaching up to 2 metres.

What is more, there were another 7 times when there were surface cracks of some 100 metres, only in the 20th century. Interestingly enough, the power of the quake did not play a significant role here. Crevices exceeding 1 km appeared during both quakes of a magnitude of 6.0 and 7.0. Smaller forms appeared in similar conditions.

Table 1

The surface-forming earthquake effects in Greece from 492 BC to 1986 AD

No	Year	Location	M	I_{max}	P	⇑	O	R	T
1	–492	Sparta	6.6	VIII			+		
2	–480	Salamis	6.3	VIII					?
3	–479	Chalcidice	7.0	?					II
4	–464	Sparta	7.0	XI	+		+		
5	–426	Fthiotis	7.0	IX				+	V
6	–373	Achaea	7.0	IX	+				VI
7	–227	Rhodes	7.2	X		+			
8	46	Thira	6.0	VI					III
9	66	Crete	7.0	X		+			III
10	142	Rhodes	7.0	X					IV
11	365	Gortyna	8.2	XI		+	+		VI
12	551	Phocis	7.2	X	+		+		IV
13	554	Kos	7.0	X					IV+
14	597	Serrai	6.8	IX				+	
15	1389	Chios	6.8	IX					IV
16	1402	Achaea	7.0	X	+				V
17	1457	Idhra	6.0	VII		+			
18	1481	Rhodes	7.2	X					IV
19	1494	Iraklion	7.2	IX					III+
20	1514	Zakinthos	6.5	VIII			+		
21	1604	Iraklion	6.8	VIII			+		
22	1612	Iraklion	7.0	VIII					III+
23	1612	Levkas	6.6	X	+				
24	1622	Zakinthos	6.6	IX	+	--			
25	1625	Levkas	6.6	IX				+	
26	1629	Crete	7.0	IX					III
27	1630	Levkas	6.6	X	+				

No	Year	Location	M	I_{max}	P	⇑	O	R	T
28	1633	Zakinthos	6.9	X	+	+	+		III
29	1636	Cephalonia	7.1	X	+	–	+		?
30	1650	Thira	6.8	VIII		±	+		?
31	1658	Cephalonia	6.8	X			?		
32	1707	Thira	6.0	VI		+			II+
33	1714	Cephalonia	6.4	VIII	+				
34	1723	Levkas	7.0	IX					II
35	1729	Zakinthos	6.5	VIII			+		
36	1731	Larisa	6.0	VIII	+				
37	1732	Corfu	6.6	VIII					II
38	1738	Milos	6.5	IX					II
39	1740	Lamia	6.5	VIII	+				
40	1748	Aegion	6.8	IX					IV
41	1758	Lamia	6.8	?		–	+		
42	1759	Thessaloniki	6.5	IX	+				
43	1767	Cephalonia	7.2	X	+		+		
44	1783	Levkas	7.0	X			+		
45	1791	Zakinthos	6.7	X					?
46	1798	Kithira	6.7	VIII	+		+		
47	1817	Aegion	6.5	X			+		IV
48	1820	Levkas	6.3	IX		–			
49	1820	Zakinthos	6.7	IX	+				II+
50	1829	Drama	7.3	X	+				
51	1831	Samos	6.0	VII			+		
52	1837	Idhra	6.2	VII			+		
53	1840	Zakinthos	6.7	X	+	±	+		
54	1843	Chalki	6.5	IX			+		IV
55	1845	Lesbos	6.8	X			+		
56	1846	Messenia	6.5	X	+				
57	1846	Samos	6.0	VIII			+		
58	1853	Thebes	6.8	X			+		II
59	1856	Iraklion	8.2	IX		–			
60	1856	Chios	6.6	IX					III
61	1858	Corinth	6.7	X	+		+		
62	1860	Samothrace	6.2	VII	+		+		
63	1861	Achaea	6.7	X	+	–	+		IV
64	1863	Chios	6.2	VIII				+	
65	1866	Thira	6.2	VIII		±			IV
66	1866	Kithira	6.8	VIII					IV
67	1867	Cephalonia	7.2	X	+				II
68	1867	Lesbos	6.8	X	+				
69	1867	Mani	7.1	IX					IV
70	1869	Simi	6.7	IX			+		
71	1869	Levkas	6.6	X					II
72	1870	Arachova	6.8	IX	+	–			

No	Year	Location	M	I_{max}	P	⇑	O	R	T
73	1872	Thesprotia	6.2	IX	+				
74	1874	Eretria	6.0	VIII			+		
75	1876	Nemea	6.0	VIII	+		+		
76	1881	Chios	6.4	XI	+	–	+		II+
77	1885	Messenia	6.1	IX			+		
78	1886	Filiatra	7.5	X	+	–			III
79	1887	Xilokastro	6.3	VIII			+		II+
80	1888	Aegion	6.2	IX	+		+		
81	1890	Psara	6.2	VII	+				
82	1893	Samothrace	6.5	IX	+	–	+		III+
83	1893	Zakinthos	6.4	IX			+		
84	1894	Lokris	7.0	X	+		+		III
85	1897	Tripolis	7.5	VII	+				
86	1899	Kiparissia	6.6	IX					III
87	1902	Thessaloniki	6.6	IX	+				
88	1903	Kithira	7.9	XI	+		+		
90	1905	Athos	7.5	X		–	+		
91	1912	Cephalonia	6.8	X	+				
92	1914	Thebes	6.0	VIII			+		
93	1914	Levkas	6.3	IX	+		+		IV
94	1915	Ithaca	6.6	IX	+	–			
95	1915	Ithaca	6.7	IX	+	–	+		III
96	1917	Navpaktos	6.0	VIII			+		
97	1918	Milos	6.6	VI	+				
98	1921	Amfilochia	6.0	VIII	+	–			
99	1926	Rhodes	8.0	XI		+			
100	1926	Sparta	7.2	VIII			+		?
101	1927	Laconia	7.1	IX			+		
102	1928	Corinth	6.3	IX	+		+		
103	1932	Ierissos	7.0	X	+	–			III
104	1938	Oropos	6.0	VIII	+		+		
105	1941	Larisa	6.3	VIII	+	–			
106	1947	Messenia	7.0	IX	+		+		II
107	1948	Karpathos	7.1	IX					IV
108	1948	Levkas	6.6	IX	+	–	+		III
109	1949	Chios	6.7	IX	+	–	+		III
110	1954	Kardhitsa	7.0	IX	+	–			
111	1955	Pelion	6.2	VIII			+		
112	1956	Amorgos	7.5	IX					V
113	1959	Mesara	6.3	VIII	+		+		
114	1959	Zakinthos	6.8	VII	+		+		
115	1965	Agrinio	6.8	VIII	+				
116	1965	Arcadia	6.1	X	+				
117	1966	Kremasta	6.2	IX			+		
118	1968	Limnos	7.1	IX					III

No	Year	Location	M	I_{max}	P	⥣	O	R	T
119	1966	Acarnania	6.0	VIII	+				
120	1973	Paleochora	6.0	VII			+		
121	1978	Thessaloniki	6.5	VIII	+				
122	1980	Almiros	6.5	VIII	+				
123	1981	Alkionides	6.7	IX	+	–	+		II
124	1983	Limnos	6.8	VI					II
125	1986	Klamata	6.0	IX	+		+		?
Sum of instances					59	30	58	3	55

According to Papazachos and Papazachos, 1989; Seismotectonic Map, ..., 1989; Karnik, 1971, Zamani and Maroukian, 1979, *Monthly Bull.*, ... 1978, 1981 and 1986, Caputo, 1993).

M — quake magnitude (in the Kanamori scale used in Greece), I_{max} — maximum quake intensity (in the MCS scale).
Observed phenomena accompanying quakes: P — surface cracks, ⥣ — local settling and falling (–) or land rising (+), O — landslides and rock falls, R — changes in the run of river beds, T — tsunamis (intensity in the Sieberg-Amvrazis scale).

Table 2 lists parameters of the largest seismic surface cracks in Greece. The fact that the activating of downcast lines on sections often significantly exceeding 1 km (joint length of these cracks is over 70 km, with drops ranging from 0.12 to 1.5 m) was documented on 9 occasions only in the 20th century, indicates a strong recurrence of these phenomena. Consequently we can see that they are clearly a relevant element in the contemporary system of sculpture transformation.

Table 2

Vertical shifts along faults registered in Greece during earthquakes

Number as in Table 1	Fault location	Last activity date	M	Lenght (km)	One-off drop (m)
36	Tyrnavos	1731	6.0	10	0.10–0.15
63	Achaea	1861	6.7	13	<2.0
72	Arachova	1870	6.8	6	1.0–2.0
84	Lokris	1894	7.0	55	1.0–1.5
93	Levkas	1914	6.3	3	1.0
103	Ierissos	1932	7.0	7	
105	Larisa	1941	6.3	12	
110	Ekkara	1954	7.0	5	0.3–1.0
117	Amfilochia	1966	6.0	2	
121	Thessaloniki	1978	6.5	12	0.3
123	Pisia	1981	6.7	15	0.6–1.5
123	Kaparelli	1981	6.3	>15	0.5–1.2
125	Kalamata	1986	6.0	6	0.12–0.18

According to Caputo, 1993; Papazachos and Papazachos, 1989.

The 20th century in Greece is not characterised by any special concentration of seismic phenomena. It should be assumed that there were cracks on the earth's sculpture proportional in size to the strength and intensity of the quakes also before. Sources in this respect are clearly incomplete, but this concept seems to be backed by the data for the second half of the 19th century (table 2), which indicates that instances of huge surface discontinuousness were formed also during that period. Their joint length (mainly due to the earthquake of 1894) also exceeded 70 km (as in the next 86-year period).

The data on strength and intensity of the quakes included in Table 1 proves that in some regions, seismic phenomena of similar parameters often reoccurred. For example, shallow quakes in Achaea, of strength and intensity compared to those of the 373 BC and 1861 AD, were registered at least 8 more times (during the 2536 year period under review). This means that there might have been surface cracks of significant size every 250 years on the average, although this was not registered by man.

The Ionian Islands are similar in this respect — if one looks at the history of Levkas, there have been at least 14 seismic catastrophes (Table 1) similar or stronger than the one in 1914. One can observe similar regularities in relation to other regions. The conclusion could be that at least 70 km of lasting surface tectonic discontinuousness are being formed in Greece during each century. The difficulty in locating them for the unregistered periods is primarily based on the fact that they are most often repetitive of older downcast forms, along which, it is impossible to establish refreshed sections without detailed dates. What is more, external processes in these areas mask the results of directly endogenous character.

Another phenomenon often registered during earthquakes is, according to table 1, the change in hypsometric location of certain surfaces. Most such cases come from the Ionian Islands, Crete and the broadly understood Gulf of Corinth coast. This means it relates mainly to regions adjacent to the western and southern borders of the Aegean Plate and areas where deep crevices in the earth's crust appear.

In most cases, events in this category were accompanied by grunt cracks (18 of 30 cases in table 1, including 9 of 11 cases in the 20th century). Earthquake directories' information on seismic deformations of surface area relates mostly to coasts, as this is where these phenomena were and are the easiest to observe.

SECONDARY SEISMIC SURFACE-FORMATION PROCESSES

The history of earthquakes in Greece has numerous examples of seismic activation of surface-formation processes of exogenous character. The secondary effect of quakes is mostly observed as gravitational mass moves (58 of 125 cases in Table 1), especially tearings, with fewer instances of landslips.

The presence of such morphogenetic results is naturally encouraged by the mountainous sculpture of Greece. Lithologic predisposition also plays a significant role. The quake strength is clearly secondary, while the presence of renewed downcast sections is very important. This regularity made itself very clear during surface formation measures of the earthquake effects of 1981 (Marinos and others, 1986) and 1986 (Mariolakos and others, 1987).

On at least 28 occasions, seismic earth surface cracks were registered along with gravitation processes, although this does not prove the cause connection of these phenomena. It is clear that the spatial distribution of landslips and breaking off created during earthquakes shows a clear correlation with sections of active downcast lines presence and a complete lack of co-ordination with the sculpture character — which plays only a secondary role when relating to gravitational mass moves of exogenous base. It is conducive to the formation of landslips, but primarily when co-operating with down falls, strong river erosion or abrasion and the human clipping of slopes, with earthquakes only last (Koukis and Ziourkas, 1989).

That is why areas most likely to suffer from seismic mass moves are those located in regions of frequent earthquakes, especially near active downcast sections. The highest Greek mountains (the Pindus chain) are nearly free from these types of phenomena, although both their sculpture, lithology and high rainfalls conduce the development of gravitation processes there, and the seismic quake intensity seems adequate.

As the most Greek regions most seismically active are clearly located near the coastline, the gravitational mass movements, being the effect of earthquakes, may be accompanied by the shifts of rock material from land to the sea bed. Written sources mention only 8 such cases. Half of these were registered on the Ionian Islands (Zante 1633 and 1729, Levkas 1914, Ithaca 1915), with no records about surface cracks only for 1729, but the epicentre of this quake was located within the sea bed.

Sources report no other data for landslips and sea breaking-offs, but it is clear that in these 8 instances, sliding or breaking away of rock and crossing the coastline accompanied by increased waves, interpreted as tsunami, occurred no less than five times.

Similar phenomena, although rarely so catastrophic, are common in Greece. They are most frequent on the Ionian Islands coastline and west Peloponnesus. Other regions liable to tsunami include the Corinthian Gulf (8 historic instances), Crete (7), the Cyclades (6), Dodecanese and northern part of the Aegean Sea (5 each), Maliakos Gulf and North-Euboean Gulf (4) and the east coastline of Chios (4). There are also references to the appearance of tsunami in the Saronic Gulf (480 BC) and Gulf of Argolis (1926). The remaining Greek coastlines also registered seismic gravitational waves, but both their size and range were closer than during average storm conditions, and so they can not be called sculpture-forming.

The morphologic meaning of tsunami, apart from extreme cases, is of relatively little significance in Greece. History knows no instances of waves breaking inland more than 1,300 metres. The average vertical range of "seismic coastline processes" reached no more than several metres. The highest given value is 25 metres (Galanopoulos 1957). This was registered on the south–east coast of the island of Amorgos in 1956, during one of the strongest shallow earthquakes to 'invade' the Aegean Sea in historic times (table 1, no. 112). This tsunami reached significant heights also on the coastlines of other islands (e.g. Astipalea — 20 m, Folegandros — 10 m), though these were undoubtedly extreme cases, appearing in Greece every several hundred years on average. Although this was only a short-lasting phenomenon, it affected a huge area. It occurred during the summer time (July 9), where strong storms are infrequent, and so its share in modelling the coastline was even larger.

During the 25-century history of observing gravitational seismic waves in Greece, the same or larger intensity of tsunamis (relating to the 5th and 6th degree in the Amvrazis-modified Sieberg scale), was registered only 5 times. A 6th degree tsunami was observed in effect of the M = 8.2 earthquake, which occurred at the western coast of Crete in 365 AD. The wave reached coastlines of Dalmatia and Egypt (this is the largest documented range achieved by a Greek tsunami).

There is even less information of the wave started by the "Minoan" eruption of Santorini. All authors agree that it circled the whole eastern part of the Mediterranean, but the estimated values do not match each other.

Historically registered instances of earthquakes in Greece include such phenomena as the variation of ground water levels (19 instances), the appearance of water and mud tanks (twice) and the change in the run of river beds (3 cases).

In most cases these were hydrological anomalies, though there is no data on their duration. The observed variations of ground water levels were not large (at least we have no credible data). It seems hard to attach a significant surface-forming role to this phenomenon.

It is also hard to call the changes in the run of the river bed as the effect of seismic quakes a primary phenomenon, as they were connected with either blocking the outflow by another directly tectonic process (e.g. a surface change or crack), or a secondary process (e.g. closing the river bed by landslips or falling of a river bank fragment), or simply, with the increase or decrease of flow due to variations of river spring fluctuations.

Summing up these considerations, one should say that the "seismic surface-forming processes," though very frequent in Greece, in the short time perspective, have nearly only local significance (apart from extreme tsunami waves). They relate to today's most active areas, and this is where they cause most changes in surface structure. However, the large repetitiveness of tectonic morphogenetic impulses makes them an important element in the system of surface modelling in the extended time scale.

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