Δελτίο Ελληνικής Γεωλογικής Εταιρίας τομ. XXX/3, 211-224, 1994
Πρακτικά 7ου Επιστημονικού Συνεδρίου, Θεσσαλονίκη, Μάιος 1994

Bulletin of the Geological Society of Greece vol. XXX/3, 211-224, 1994
Proceedings of the 7th Congress, Thessaloniki, May 1994

THE AMOUNT OF EXHALATIVE-SEDIMENTARY DEPOSITS RICH IN Fe, Mn, P AND Ba AT SANTORINI

K. Boström* and N. Arvanitides**

ABSTRACT

Sediments in hot spring-bays on the Kameni islands, in the Santorini caldera and in the drill-hole GPK-1 are rich in valcanogenic Fe, Mn, P, and Ba. The rapid supply of hydrothermal matter should have overfilled the biggest bay several times since its origin in 1870. Most of the hydrothermal matter has overflown into the caldera or the Mediterranean. Also, even pre-Kameni age sediments contain huge excesses of Fe, P, Mn, and Ba, indicating that just after the Minoan eruption the metallogenetic processes were several hundred times faster than at present.

INTRODUCTION

Hydrothermal processes and hot springs are of interest as potential heat sources and for the modelling of geological events, such as metasomatism and deposition of metalliferous deposits (Allen and Day, 1935; Naboko, 1963; Waring, 1965; Bischoff, 1969; Zelenov, 1964, 1972; Boström, 1980; Cronan, 1980; Rona, 1988; White et al,, 1988 Von Damm, 1990 and Boström 1991). The metalliferous sediments at Santorini have been the object for several studies (Brun, 1911; Harder, 1964; Butuzova, 1969; Bonatti et al., 1972; Puchelt, 1973; Puchelt et al., 1973; Petersen and Müller, 1978; Smith and Cronan, 1978, 1983; Boström and Widenfalk, 1984, Boström et al., 1990 a, b, c, d and Varnavas et al., 1990, 1991). Such studies can be carried out more easily on Santorini than in many other island arc settings for logistic reasons.

Furthermore, a long drillcore on Palea Kameni reveals that metlliferous processes took place before Palea Kameni was formed, and may have started at the Minoan eruption around 1600 BC (Arvanitides et al., 1990). The first metlliferous hot springs probably appeared at the onset of volcanism on Thera some 1.6 m.y. ago (Ferrara et al., 1980), but little is known about this early epoch.

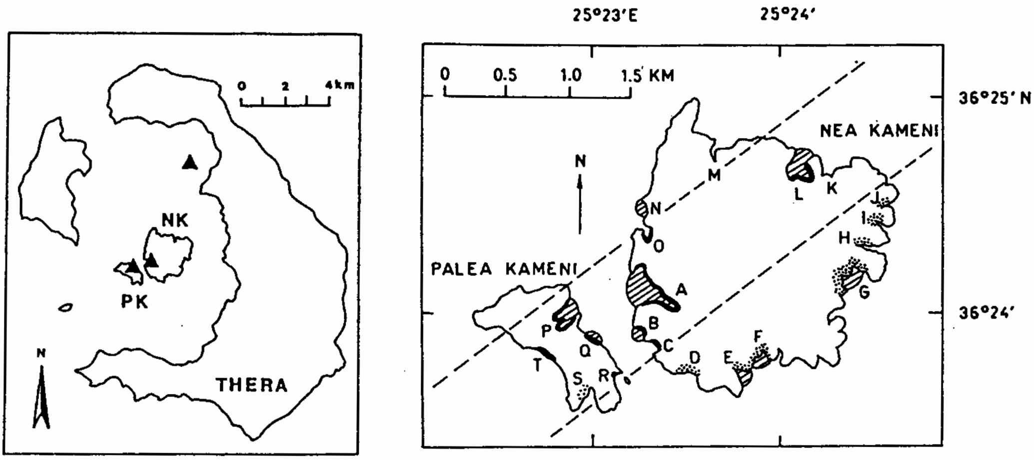
However, the supply rates of these hydrothermal solutions have only received limited attention. Petersen and Müller (1978) estimated the amount of hydrothermal Fe and Mn that deposited at Santorini during 550 years, and Boström et al., (1990a) showed that the A-bay (Fig 1) on Nea Kameni should have overfilled several times with hydrothermal muds since 1870 when the bay was formed (Fouqué, 1879). Findings of excess Mn in the Aegean Sea (Varnavas, 1989) are additional reasons for a renewed study of these

* Department of Geology and Geochemistry, Stockholm University, 106 91 Stockholm, Sweden

** Institute of Geological and Mineral Exploration, 1 Fragon Str., 546 26 Thessaloniki, Greece

quantitative problems.

A problem with such quantitative studies is that rapidly depositing volcanoclastic matter suppresses the exhalative signals; even small analytical errors makes it hard to conclusively detect volcanogenic matter. Also, preliminary studies in the West Indies, e.g. at the submarine volcano Kick'em Jenny (K.B., unpubl. data), reveal that the lack of good catchment basins makes it difficult to make quantitative estimates; similar relations are common at many other island arcs (Zelenov, 1972). Santorini on the other hand is exceptionally well suited for such studies because its big caldera acts as a trap.



A B

Fig 1: (A) General map of the Santorini islands, of which the two biggest, Thera and Therasia are part of a ringformed structure around the caldera depression with the two central islands Palea and Nea Kameni. Triangles show areas with major hydrothermal discharges.
Fig (B) Distribution of hot springs and related phenomena on the Kameni islands. Heavy black shading indicates shorelines with strong staining from volcanic ferric hydroxides, stippled shading shows shore lines with weak staining, and shaded water areas represent outflowing water masses with strong discoloration from hydrothermal activities. Dashed lines show boundaries of the zone with major hydrothermal springs (Fouqué, 1879; Heiken and McCoy, 1984). A to T represent sites with distinct hydrothermal activity (except for bay M, see text).

GENERAL GEOLOGICAL BACKGROUND AND FIELD RELATIONS AT SANTORINI

The Santorini group of islands is located on the calc-alkaline Hellenic Volcanic arc, which stretches from Aegina and Methana in the west over Milos and Santorini and terminates at Yali and Nisyros in the east (Papavassiliou et al., 1990). Indications of hydrothermal processes are of two types, namely:

a) present hydrothermal discharges, including carbon dioxide rich emanations at Methana, iron manganese-rich solutions on Santorini and very acid solutions on Yali, and

b) fossil evidence, including old hydrothermal deposits at Vani, which are rich in iron, manganese and barium (Liakopoulos, 1987; Galanopoulos and

Koinakis, 1991; Boström and Galanopoulos, 1994) and hydrothermal iron-rich ash-beds that predate the formation of the Kameni islands (Arvanitides et al., 1990).

A. Recent hydrothermal processes

The major islands of Thera and Therasia form a circular feature around a caldera, in which the post-caldera, in which the post-caldera islands Palea and Nea Kameni are located; the structure of the caldera depression has been discussed by Perissoratis (1990). Recent active hot springs occur in this caldera (Figs 1a, b), the most intense ones being found at the bays A and P, using a modified nomenclature by Butuzova (1969). There are further-more strong indications of an intense hot spring area in the more strong indications of an intense hot spring area in the caldera (Fig 1A; Perissoratis et al., 1990; Boström et al., 1990d). Brick red staining of shore lines, discolored waters (greysish-greenish-white, or sometimes even yellowish or reddish brown) and accumulation of red or brown muds reveal the existence of many hot springs on Palea and Nea Kameni, see Fig 1B. Some mud deposits are particularly large, namely at A, G, L and P, partly because of the protection that long and narrow bays offer. In more exposed bays, on the other hand, winds and waves have prevented the build-up of larger hydrothermal deposits, for instance at C, D, Q and T. These observations (Boström and Ingri, unpubl. data) verify those by Butuzova (1969), except for bay M where no indications were found.

The P-bay is the best studied bay on the Kameni islands (Puchelt, 1973), partly for logistical reasons; its outer part is easily accessible with 10-30 m long boats and walking on the shores is easy. The emanations appear as intense bubbling in the inner part of the bay (Varnavas et al., 1990), but spring openings with easily measurable flows are hard to identify. The P-bay hot spring waters show lower Fe and Mn contents than the springs from the inner basin in the A-bay (Varnavas et al., 1990); yet, these results indicate a very active hydrothermal source for the solutions also in the p-bay. Furthermore, hot spring waters in drillhole GPK-1 (some 40M NE of the innermost part of the bay, see Boström et al., 1990b) show a chemical composition similar to that of the springs in the A-pay. Similar difficulties were encountered in bay G in 1988, where easily sampled red-brown muds and discolored hydrothermal waters occur, but no easily measured spring orifices were found.

The A-bay is about 350 m long and has a wide, funnelshaped mouth, that narrows rapidly and is quite constricted about 220 m form the mouth. The innermost 50 m are slightly broader, forming an inner basin, which has most of the sediments in the A-bay (Fig 2). At the eastern terminus of this inner basin there is a little pumice beach, some 2 by 4 m in dimensions. The A-bay has been much less studied than the P-bay, although the springs there are the most conspicious of all at Santorini. However, Fouqué (1879) remarked on the blocky lava flows, which make walking very awkward, and approach by water can only be made in small boats because of the narrowness of the inner 130 m of the A-bay. Also, the beaches are generally very steep, numerous slopes being 25-35^{o} and are made up of boulders and blocks, mostly some 20-80 cm in diameter. In essence the A-bay is a gorge between two lava flows, the Aphroessa lavas of 1866-1867 to the north and the Giorgios lavas of 1870 to the south (Fouqué, 1879); subsequent lavas of 1939-1941 (Fytikas et al, 1990), have left the shore lines from 1870 intact (Fouqué, 1879, Plate XXIX and page 173). The depths have changed little since 1870, indicating a

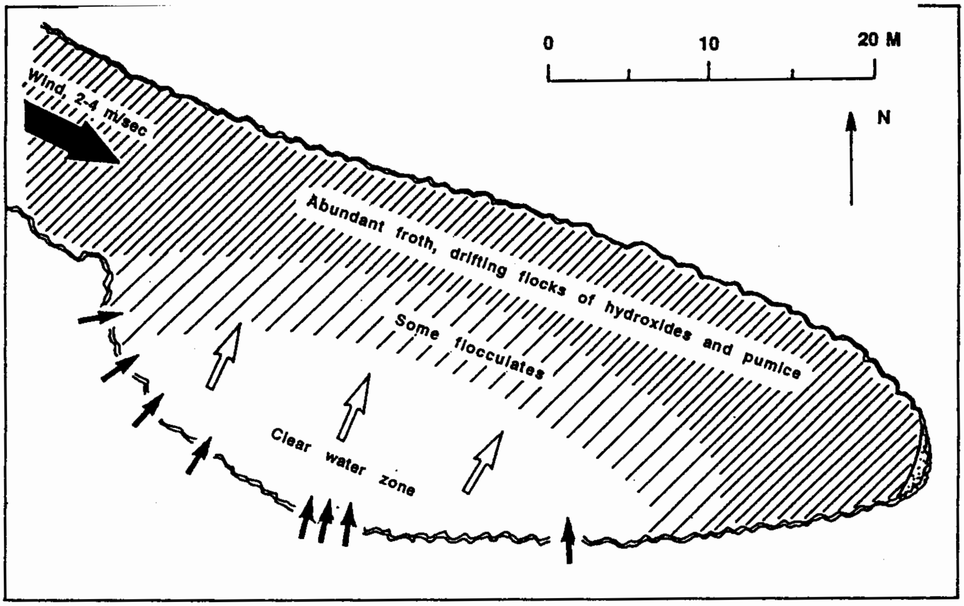


Fig. 2: Inner basin of bay A. The clear water zone is near the shore with the strongest hot spring discharges. Intensity of shading indicates degree of surface coverage of froth, bubbles, floating flocculates and pumice. Big black arrow shows prevailing wind during the measurements (2-4 m/sec), small black arrows indicate measured springs and big open arrows show the general flowdirection of the clear water zone.

negligible net accumulation in the A-bay.

The inner basin is well protected form winds and strong waves, but water line marks in the form of pumice-streaks 45 cm above the calm weather water surface indicate that storms can raise the water level considerably; abundant pumice at the 0-30 cm level suggests that such storm levels are common. The subsequent evacuation of the waters should cause major abrasion, hence only soft sediments deposited below the silldepth of the inner basin can remain (Boström and Ingri, unpubl. results). The transport of pumice-beach, most pumice probably entering by floating; aeolian transport of coarse pumice is unlikely. That storms play a big transporting and sorting role on the Kameni islands is obvious form from the beach terraces of pebbles, stones and small blocks on Nea kameni near bays M to O and D to E, which face the NW and SW gaps between the major Santorini islands.

B. Fossil indications of hydrothermal processes

The lowest part of core GPK-1 (interval 155-200 m; Arvanitides et al., 1990) is rich in excess iron, and some excess manganese, phosphorus and barium and will be further discussed below.

FIELD WORK

To further refine our studies one of us (K.B.) went to the A-bay, Nea Kameni, in Oct 1993 to measure flow rates from the springs and to study the distribution of hot springs better. The lack of detailed maps of the A-bay make all measurements approximate, but a map form the Greek Geological Survey (IGME) on a scale of 1:5000 suggests that the description below is reasonably accurate. Lack of good maps has considerably hampered many other studies of this bay. The weather was calm during the visit; in the inner bay there was only a faint chop and wind (2-4 m/sec) which was favorable for the measurements.

All hot springs with measurable flows occur on the southern shore of the inner basin, most on the western half of the shore line, see Fig 2. Much hydrothermal matter, such as flakes of ferric hydroxides and siliceous particles drift away form this zone and accumulate against the northern shore and the eastern terminus of the bay, forming a zone with almost clear water surface next to the springs. This clear water zone is conspicuous and seems to be a permanent phenomenon weather permitting and has been observed at all ten field visits since 1982. Many springs are easily detected because of their individual appearance, being coated in their inner parts with white siliceous matter, reddish brown coatings and mats of sap-green algae(?). Some springs have formed pinkish coatings on nearby boulders. Other springs lack siliceous precipitates and some may show a mat of ferric hydroxydes only, see Table 1. These results suggest that there is a gradual change in the hot water chemistry; future analyses should test this impression. Photographic recordings of the whole southern shore reveal that there are about 38 spring openings, 28 of them on the westernmost 25 m of the shore, another 10 openings in a 10 m-section further east and none (?) in the last 15 m-stretch of this shore. These figures are approximate; anastomosing currents around some big boulders make it hard to separate individual sources. All springs debouch 0-2 cm below the water surface.

Table 1: Data for hot springs at inner basin of bay A, Nea Kameni

Spring No	Type	Thermocline	Discharge rate depth (cm)	Comments (L/min)
1	B	>15	23	FSU
2	A	20	640	SF
3	A	35	410	SF
4	A	40	140	S *
5	A	25	464	SF
6	A	25	20	FSU
7	A	25	516	SF
8	C	25-40**	191	SF

All springs occur on the SW shore line of the inner basin, spring No 1 being located toward W and No 8 furthest E. All flowrates are mean data from at least three measurements. Springs 5, 6 and 7 are very closely spaced, about 4 m form each other, but may represent different springs since their flow rates vary considerably.

Type A springs have well developed white (siliceous matter), green (algae) and brown (ferric hydroxide) coatings around the orifices, whereas type B spring have green an brown coatings, and type C only brown deposits at the orifices.

* Distinct whirring sound in the spring.

** The thermocline was eddy and hard to measure well, in sharp contrast to the situation at other sites.

Discharges occur also on the northern and eastern shores of the inner basin, but consist there primarily of gas bubbles (CO2?), that mostly are released in short sporadic bursts, and may partly represent bacterial products. The flow rates are very low, and do not displace particles and debris in the surface layers; their flows are therefore hard to measure. However, bubbly springs may deliver much hydrothermal matter (Varnavas et al., 1990).

Table 2: Analyses of standard basalt BHVO-1

Rock	BHVO-1 SU	BHVO-1 LU	BHVO-1 Rec value
SiO_2	49,88	49,00	49,94
Al_2O_3	13,88	13,90	13,80
Fe_2O_3	12,44	12,20	12,23
MnO	0,173	0,173	0,168
MgO	7,35	7,39	7,23
CaO	11,41	11,40	11,40
Na_2O	2,25	2,35	2,26
K_2O	0,49	0,42	0,52
TiO_2	2,73	2,81	2,71
P_2O_5	0,27	0,31	0,27
Ba	0,0135	0,0136	0,0139
Total oxides	100,87	99,95	100,53
Cr	308	302	289
Zr	165	161	179
Sr	396	392	403
Cu	136	117	136
V	317	311	317
Zn	115	94	105
La	17	18	16
Y	29	27	28
Yb	1,9	2	2,0

Note: All major elements (SiO_2-Total oxides) are given in wt.%, all traces (Cr-Yb) in ppm. SU=analyses made at Stockholm University, LU = analyses made at SGAB, Lulea, Rec value = recommended value.

Flow measurements were made in tow ways, using a folding rule with centimeter scale and an electronic stop-watch, all timings being made in triplicate or more: 1) by measurements at individual spring orifices and by subsequent addition of obtained results or 2) by measuring the flow rate of the clear water zone.

1. Clocking the flow rates of individual particles in the water, and measuring the dimensions of a given flow channel permitted the calculation of flowrates (in L/min); in deep channels also the thermocline was measured, that is, the sharp boundary between the 34°C warn outflowing surface layer and the colder (about 20°C) water below. The measurements were made at the eight strongest springs, see Table 1. The total outflow is about 2400 L/min, but this value may be somewhat large, since occasional backflows among big boulders are hard to estimate.

2. Flow rates in the clear water zone were measured, using small particles that were spotted some 10-20 cm from the southern shore and then followed as they drifted 50-100 cm to the NNE. The flow of 25cm/min appeared to be fairly unidirectional without eddies or whirls; the thermocline was located at a depth of 25 cm. The outflow in the clear water zone is thus 2200L/min.

Method 1 and 2 thus yield similar results. We will here use the more conservative estimate of 2000L/min. However, these measurements do not consider temporal meteorological effects (Varnavas et al., 1990).

AMOUNT OF HYDROTHERMAL INPUT AT INNER BASIN

The chemical composition of the hot spring waters in drill hole GPK-1 and

Table 3: Distribution models for excess Fe and Mn at Santorini

	Exc Fe (Tons)	Exc Mn (Tons)
Quantities delivered by hot spring flows of 6000L/minduring 120 years; data from this paper	5.300	470
Quantities delivered by hot spring flows of 6000L/min during 550 years; data from this paper	24.300	2.200
Quantities delivered during 550 years in a 45 cm thick layer in the caldera (Petersen and Müller, 1978)	304.000	19.000
Quantities present in a 45 cm thick layer in the caldera, using excess data for 14 sediment samples (Boström et al., 1990d)	379.000	18.700
Quantities present in 45 m thick layer in thecaldera, using excess data in Table X (Based on analyses in Arvanitides et al., 1990)	33.090.000	74.600

in the A-bay are very similar (Boström et al., 1990 b, c), suggesting that all springs have a common source at a depth far below 200 m, which is the bottom depth for GPK-1 (Arvanitides et al., 1990). The discharging waters may deposit about 100 mg/L solid components (Boström et al., 1990 b, c) including 52 mg SiO_2, 27 mg $Fe(OH)_3$, 2.4 mg $Mn(OH)_3$, 0.092 mg $BaSO_4$ and 0.76 mg Ca5 $(PO_4)3OH$, and 18 mg of other components. These values are good approximations of the deposited matter, but selective losses may take place as discussed below.

The inner basin delivers about 2000L/min of hot spring water, and may thus deposit about 105 tons of volcanogenic mud per year. The dry in situ uncompressed density (DISUD) of loose muds is generally about 0.5g/cm^3, and the sediment surface area of the inner bay is 550 m^2, that is, during one year the sediment surface should rise 38 cm if the quantitative accumulation of hydrothermal matter was undisturbed. The inner basin should consequently fill up in about 10-20 years, corresponding to a sediment pile of 23 m if the hot spring activities had been constant the last 120 years and assuming that the total mud pile has a DISUD-value of 1.0g/cm^3. The present sediment content of the inner basin is about 500 tons, based on the areal extent, the slopes of the shore lines and the depth of the sediment surfaces, which is at a depth of 2 m.

PRESENT SUPPLY RATES OF HYDROTHERMAL MATTER AT SANTORINI

It is obvious that only little sedimentary matter accumulates in the A-bay, about 95% being lost to caldera and elsewhere. However, the ubiquitous iron stained shore lines and volcanic mud-filled bays, large discolored water zones and the new spring system in the caldera, indicate that additional vigorous hydrothermal vents exist at Santorini.

Lack of calm waters make spring studies difficult in the remaining part of the A-bay, but it seems reasonable that some 500L/min are seeping out there, and that the P-bay with its massive sediment pack receives a considerable inflow of hydrothermal water, perhaps 1000L/min; the discolored sea water zone outside the p-bay is quite extensive (Fig 1) and may sometime reach far out into the channel between the Kameni islands. Other bays on the Kameni islands appear to have weak flow rates, but may together match the flows assumed for the P-bay, judging from accumulated sediments and discolored seawater plumes. The NE part of the caldera also has a hydrothermal spring with sizeable flow, as the marked anomalies of excess iron, manganese, barium and phosphorus anomalies of excess iron, manganese, barium and phosphorus indicate (Perissoratis et al., 1990, Boström et al., 1990d). Thus, the discharge of hydrothermal solutions in the Santorini caldera may at present be at least 6000L/min, suggesting that about 37.800 tons of hydrothermal matter was deposited during the last 120 years; most of this has left the hot spring bays and occurs in the caldera and outside the Santorini archipelago.

The total caldera floor has changed little the last 120 years, the flat deep, sediment accumulating areas covering about 25 Km^2. This implies that 0.15 g of volcanic mud has deposited per cm^2 the last 120 years, corresponding to a layer of about 0.30 cm, or about 8.8 cm since the formation of the present caldera 3500 years ago. The caldera deposits are mainly mixtures of pumice and hydrothermal matter in the proportions 10:1-20:1 (Boström et al., 1990d), corresponding to an accumulation of much less than 80 cm, since addition of pumice to the loose hydrothermal fraction increases the sediment density considerably. However, this value is far too low, even considering the fact that deposition rates in the caldera were much higher about 3000 years ago than at present; thus Perissoratis (1990) showed that the seismically transparent sediments formed after the Minoan eruption are about 2-3 m in thickness.

Petersen and Müller (1978) estimated the volcanic excess iron to be 304.000 tons and 19.000 tons for Mn, assuming that the deposition took place in 550 years, forming the upper 45 cm of the caldera deposits. This estimate is larger than the supply of 6000L/min suggests, yielding a total of 24.300 tons of excess Fe and 2.200 tons of excess Mn.

Excess data for Fe (1.98%) Mn (0.098%), P (0.039%) and Ba (0.0024%) were derived form data in Boström et al (1990d) for the Recent caldera sediments. (There is a strong need for good analytical data, since pumice frequently depresses the hydrothermal signal. Table 2 shows standard rock studies by the analytical laboratories, that produced the data for this paper, revealing an excellent quality). Using these excess values for Fe, Mn, Ba and P and assuming that the thickness of the late deposits is about 2.5 m (Perissoratis, 1990) we find that the excesses represent 2.104.000 tons of iron, 104.000 tons of manganese, 41.000 tons of phosphorus and 2.500 tons of barium. However, some of these values may be 4-5 times too large since excess Mn for instance is much lower at depth than in the surface layer (Petersen and Müller, 1978; Smith and Cronan, 1978). Assuming the added layer to be 45 cm we find excess data similar to those in Petersen and Müller (Table 3).

PAST DEPOSITION RATES OF HYDTROTHERMAL MATTER

There are strong reasons to assume that the hydrothermal discharge rates were much higher in the past. Fouqué (1979, Plate XXIX) indicated more than 150 fumaroles with temperatures of 100-300°C, and at least five "red glowing" fumaroles on the lavafields. Numerous hot springs with temperatures below 50°C were found in several bays and channels, and many sites with discolored ferruginous waters of 60-70°C were listed by Fouqué where none exist today. These facts suggest that the large-scale hydrothermal activity in the caldera has decreased considerably since the Minoan eruption, although with resurging activities during major volcanic events, which initiated the formation of Palea Kameni at 197 BC and caused the outflow of the Georgios lavas 1866-1870 (Fytikas et al., 1990). Flow rates of 6000L/min are hence not characteristic for the early period after the Minoan eruption.

This conclusion is corroborated by the findings of iron-rich ash beds below the Palea Kameni lavas (Arvanitides et al., 1990), revealing that the hydrothermal contribution of Fe, Mn, P, and Ba appeared much earlier than 550 years ago. Indeed, the sediments found under the lavas on Palea Kameni in drill hole GPK-1 make up at least 45 m (the core terminated in the sediment layer), not 0.45-2.5 m as assumed above. This discrepancy is probably due to the fact that immediately after the big Minoan eruption much pumice and other volcanoclastic matter was swept down into the caldera depression, a process that largely took place the first decades or centuries after the eruption. The early hydrothermal processes were probably very intense; thus data form drillhole GPK-1 show that these sediments were distinctly enriched in iron, manganese, barium and phosphorus, see Table 4 and Figs 3 and 4. However, the heavy admixture of pumice make them less transparent, resulting in a large underestimation of the hydrothermal components.

It appears likely that these excess values are low compared to what is characteristic for the sediments that cover the whole caldera floor ($25Km^2$) to a depth of at least 45 m; it is unlikely that easily dispersed hydrothermal matter would accumulate only on top of a seamount that later would burst the surface and form the Kameni islands; numerous studies of deep sea floor deposits show that tops of seamounts generally are poor in loose metalliferous deposits (Menard, 1964; Boström, unpubl. data). These relations and an assumed DISUD-value of 1.7 g/cm^3 for the pumice rich deposits, yield the excess quantities shown in Tables 3 and 5, which are much larger than any previous estimate. These excess quantities would furthermore require discharge rates that are about 250 times larger than at present, or even more if some iron has left the caldera. However, as is shown above these estimates are probably far too low.

The proportions of Fe, Mn etc. in hot spring waters from the Nea Kameni springs suggest that much more Mn, P and Ba should depost in the caldera than is obvious from Table 3; these losses are distinct for Mn (97%), but also much Ba (66%) escapes from Santorini, see Table 5. This behaviour is partly to be expected from the distribution of excess Mn in the GPK-1 core, see Fig 4. These patterns suggest that there are selective losses of Mn from deeper layers due to redox processes, or that the early volcanic periods discharged much less Mn and Ba. However, it is difficult to imagine the early phases to be iron dominated to such an extent as the small deposition of excess Mn in GPK-1 suggests; it is more likely that postdepositional migrations of Mn and selective losses in the water phase of Mn and Ba better explain this paucity of Mn and Ba. Such behaviours are well known form embayments were reducing conditions have developed at depth in sediments and water masses. These migration patterns do also better explain the large excesses of Mn and Ba, found in pelagic sediments.

CONCLUSIONS

The hydrothermal discharge rates at Santorini have decreased consider-

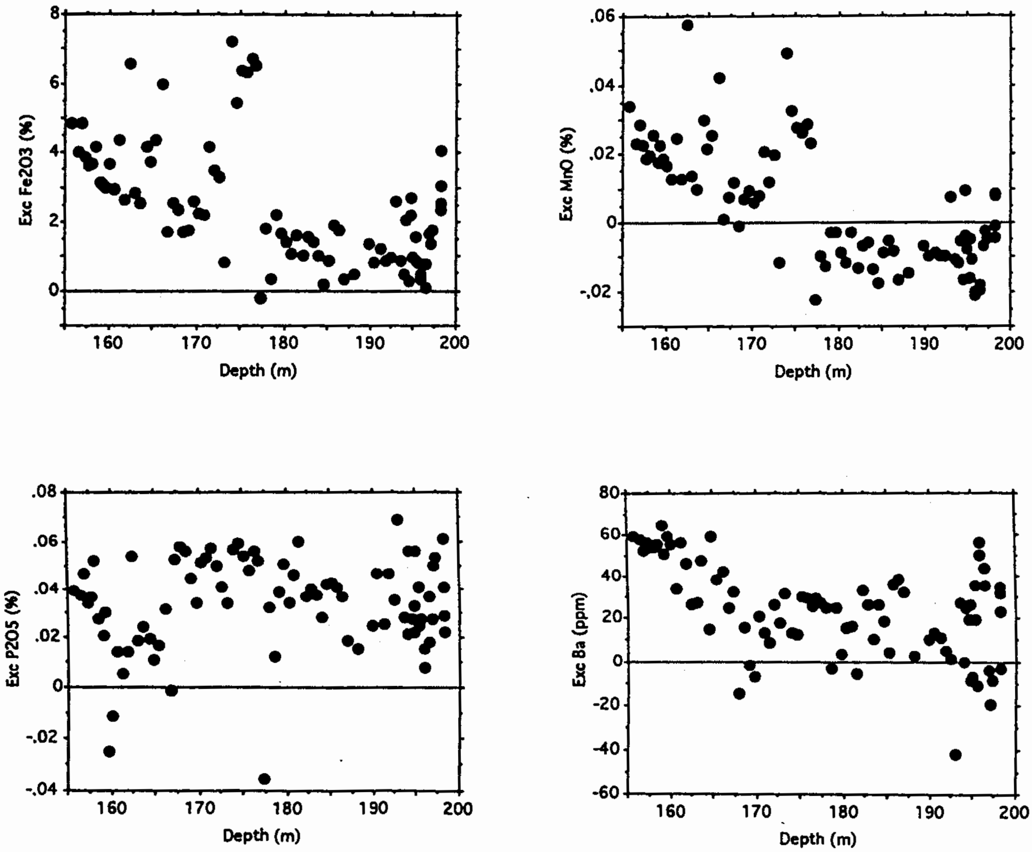


Fig. 3: Relations between excess iron, manganese, phosphorus and barium versus depth in drill core GPK-1; based on data in Arvanitides et al., (1990), for details, see text.

ably since the big Minoan eruption some 3500 years ago. Present discharge rate of metalliferous spring waters may be close to 6000L/min, a value that easily explains the formation of present metalliferous muds on Palea and Nea Kameni, as well as surface deposits at depths in the caldera, but which can explain only a minute fraction of all the exhalative matter found in the pumice beds that predate the formation of the Kameni islands. Most likely the early the formation of the Kameni islands. Most likely the early hydrothermal processes just after the Minoan eruption had an intensity that was 200 - 1000 times stronger than at present.

ACKNOWLEDGEMENTS

This research has been supported by IGME and by funds from NFR (=Swedish natural sciences research foundation). We also want to thank Dr Johan Ingri

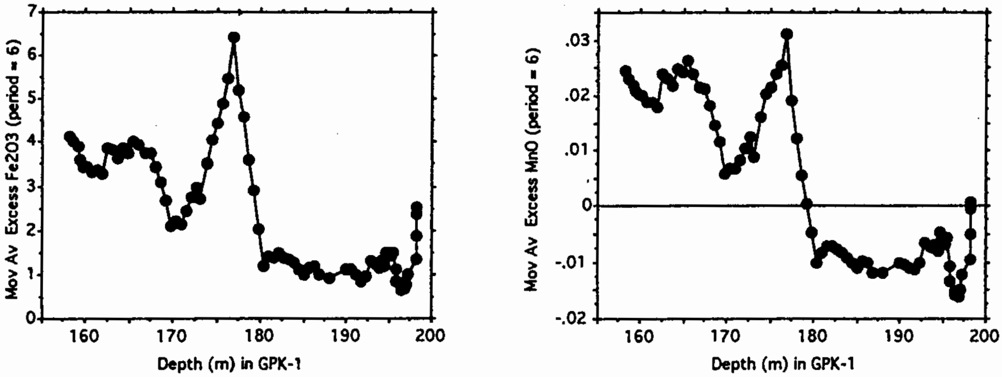


Fig. 4: Moving average data for excess iron and manganese versus depth. Note the sharp maxima at about 157m, 163m, 166m, 177m, 195m and at 198m. Based on data in Arvanitides et al., (1990), moving period is 6.

Table 4: Composition of volcanic sediments from core GPK-1

Layer	Section A 155-177 m		Section B 177-200 m		Total		Pumice
	x	s.e	x	s.e	x	s.e.	
Al_2O_3(%)	14,3	0,1	15,1	0,1	14,7	0,1	17,1
Fe_2O_3	9,1	0,2	6,9	0,1	7,9	0,2	6,31
Exc.Fe_2O_3(%)	3,8	0,3	1,3	0,1	2,5	0,2	-
MnO(%)	0,15	0,002	0,13	0,001	0,14	0,001	0,16
Exc.MnO(%)	0,02	0,002	-0,009	0,001	0,005	0,002	-
P_2O_5(%)	0,16	0,003	0,17	0,003	0,034	0,002	0,15
Exc.P_2O_5(%)	0,035	0,003	0,34	0,003	0,034	0,002	-
Ba(ppm)	353	3	354	2	353	2	382
Exc.Ba (ppm)	34	3	15	3	24	2	-
n	39		45		84		

All data from Arvanitides et al., 1990. X represents mean arithmetic value, s.e. standard error, that is, standard deviation divided by square root of n, which represents number of datapoints, s.e. is useful in the student t-test of mean values. Data for GPK-1 sediments from Arvanitides et al., 1990; data for pumice from Boström et al., 1990a.

Table 5: Total volcanic components in the Santorini caldera

	Excess content (in %)	Excess content in 1000 tons	Contents in NKHSW (µg/L)	Expected excess in 1000 tons	Real excess in % of expected	Lost from caldera (in % of expected
Exc. Fe	1,74	33 300	13476	33 300	100	0
Exc. Mn	0,0039	75	1198	2960	2,5	97,5
Exc. P	0,015	296	140	346	86	14
Exc. Ba	0,0024	46	54	133	34	66

Excess content from Table 3; Real content calculated from assumption that caldera basin is 25 km3 and ashbed is 45 m thick and density 1.7. NKHSW represents contents in waters from the Nea Kameni Hot Spring Water from inner basin (After Boström et al., 1990c). Expected content shows how much Mn, P and Ba would have deposited, had the hot spring waters deposited their contents without selective losses.

for assistance in the field and valuable discussions of these questions. We also want to thank all unknown reviewers for most valuable comments on the early draft of this manuscript.

REFERENCES

ALLEN, E. T. and DAY, A. L. (1935). Hot springs of the Yellowstone National Park. Carnegie Inst. of Washington, publ. 466, 1-525.

ARVANITIDES, N., BOSTRÖM, K., KALOGEROPOULOS, S., PARITSIS, S., GALANOPOULOS, V. and PAPAVASSILIOU, C. (1990). Geochemistry of lavas, pumice and veins in drill core GPK-1, Palea Kameni, Santorini. In Thera and the Aegean World III 2., Thera Foundation, London, 266-279.

BISCHOFF, J. L., (1969). Red Sea geothermal brine deposits. In E. T. Degens and D. A. Ross (eds): Hot brines and recent heavy metal deposits in the Red Sea. Springer Verlag, New York, 368-401.

BOSTRÖM, K. (1980). The origin of ferromanganoan active ridge sediments. In: Sea floor-spreading centers-Hydro-thermal systems. Benchmark papers in Geology, 56, (Ed: s P.A.RONA, P. LOWELL) 288-332.

BOSTRÖM, K., (1991). Hydrothermal processes at young island arcs and other areas. Mem. Soc. Geol. Italiana, 41, 209-217.

BOSTRÖM, K., HALLBERG, A., ABERG, A., ABERG, and MAGNÉT de SAISSY. (1990a). Metallogenesis at Santorini - A subduction zone related process. I: Deposition of hydrothermal sediments. In Thera and the Aegean World IiI 2., Thera Foundation, London, 280-290.

BOSTRÖM, K., Ingri, J., BOSTRÖM, B., ANDERSSON, P., ARVANITI-DES, N., GALANOPOULOS, V., KALOGEROPPOULOS, S., PAPAVASSILIOU, C. and PARITSIS, S. (1990b). Chemistry of hydrothermal solutions in drill hole GPK-1, Palea Kameni, Santorini, Greece. In Thera and the Aegean World III2., Thera Foundation, London, 257-260.

BOSTRÖM, K., INGRI, J., BOSTRÖM, B., ANDERSSON, P. and LÖFVENDAHL, R. (1990c). Metallogenesis at Santorini - A subduction zone related process. II: Geochemistry and origin of hydrothermal solutions on Nea Kameni, Santorini, Greece. In Thera and the Aegean World III2., Thera Foundation, London, 280-290.

BOSTRÖM, K., PERISSOTIW, C., GALANOPOULOS, V., PAPAVASSILIOU, C., BOSTRÖM, B., Ingri, J. and Kalogeropoulos, S. (1990d). Geochemistry and structural control of hydrothermal sediments in the caldera of Santorini. In Thera and the Aegean World III 2., Thera Foundation, London, 325-336.

BOSTRÖM, K. and GALANOPOULOS, V. 1994. The origin of volcanic-exhalative deposits rich in Fe, Mn and Ba; a comparison of the Vani and the Langban deposits. Trans. Of the Greek Geol. Congress 1994, this volume.

BRUN, A. (1911). Recherches sur l' exhalation volcanique, Paris.

BUTUZOVA, G. Yu. (1969). Recent volcano-sedimentary iron-ore process in Santorini volcano caldera and its effect on the geochemistry of sediments. Transactions, vol 194, Akad.Sciences, USSR, Geological Institute. (in Russian)

FERRARA, G., FYTIKAS, M., GIULIANI, O. and MARINELLI, G. (1980). Age of formation of the Aegean active volcanic arc. In Doumas (Ed) Thera and the Aegean World II, 37-41.

FOUQUÉ, F. (1879). Santorini et ses eruptions, Paris.

FYTIKAS, M., KOLIOS, N. and VOUGIOUKALAKIS, G. (1990). Post-minoan volcanic activity of the Santorini volcano. Volcanic hazard and risk, forecasting possibilities. In Thera and the Aegean World III 2., Thera Foundation, London, 183-198.

GALANOPOULOS, V. P. and KOINAKIS, I. (1991). The hydrothermal mineralisation at Vani, Milos. Internal IGME-report.

HEIKEN, G. and McCOY, F. (1984). Caldera development during the Minoan eruption, Thera, Cyclades, Greece. J. Geophys. Res., 89, 8441-8462.

LIAKOPOULOS, A. (1987). Hydrothermalisme et Mineralisation Metalliferes de l'isles Milos. These Universite Pierre et Marie Curie, Paris.

MENARD, W. (1964). Geology of the Pacific Ocean. McGraw-Hill, New York.

PAPAVASSILIOU, C., BOSTRÖM, K., PARITSIS, S., GALANOPOULOS, V., ARVANITIDES, N. and KALOGEROPOULOS, S. (1990). Drilling of an ore-forming shallow hydrothermal system, Santorini volcano, Greece. In Thera and the Aegean World III 2., Thera Foundation, London, 250-256.

PERISSORATIS, C. (1990). Marine gelogical research on Santorini: preliminary results. In Thera and the Aegean World III 2., Thera Foundation, London, 305-311.

PERISSORATIS, C., ANGELOPOULOS, I. and ZACHARAKI, P. (1990). Petrographic description of marine sediments form Santorini: Evidence for a new submarine hot spring field in the bottom of the caldera. In Thera and the Aegean World III 2., Thera Foundation, London, 300-304.

PETERSEN, M. D. and MÜLLER, G. (1978). Recent tuffitic sediments around Santorini, Greece, in Doumas (Ed) Thera and the Aegean World I, 311-332.

PUCHELT, H. (1973). Recent iron ore sediment formation at the Kameni islands, Santorini, Greece. In G. C. Amstutz and A. J. Bernal (eds). Ores in sediments, Berlin, 227-245.

RONA, P. A. (1988). Hydrothermal mineralisation at ocanic ridges. Can. Mineralogist, 26, 431-465.

ROSENBAUTER, R. J. and BISCHOFF, J. L., 1983. Uptake and transport of heavy metals by heated seawater: A summary of experimental results In: Hydrothermal processes at seafloor spreading centers, (Ed:s P. A. Rona, K. Boström, L. Laubier and K. L. Smith), 177-198.

SMITH, P. A. and CRONAN, D. S. (1978). Geochemical dispersion of metals in and around the caldera of Thera, in C. Doumas (ed) Thera and the Aegean World I, 343-361.

SMITH, P. A. and CRONAN, D. S. (1983). The geochemistry of metalliferous sediments and waters associated with shallow submarine hydrothermal activity (Santorini, Aegean Sea). Chem Geol., 39, 241-262.

VARNAVAS, S. P. (1989). Submarine hydrothermal metallogenesis associated with the collision of two plates: The southern Aegean region. Geochim. Cosmochim. Acta, 53, 1-15.

VARNAVAS, S., CRONAN, D. and ANDERSON, R. K. (1990). Spatial and time series analysis of Santorini hydrothermal waters. In Thera and the Aegean World III 2., Thera Foundation, London, 312-324.

VARNAVAS, S. R., and CRONAN, D.S. (1991). Hydrothermal metallogenetic processes off the islands of Nisyros and Kos in the Hellenic Volcanic Arc. Mar. Geol., 99: 109-133.

VON DAMM, K. I. (1990). Sea-floor hydrothermal activity: Black smoker chemistry and chimneys. In G. W. Wetherill, A. L. Albee & F. G. Stehli (eds) Annual Review of Earth and Planetary Sciences, 18, 173-204.

WARING, G. A. (1965). Thermal springs of the United States and Other Countries of the World - A Summary. Revised by R. D. Blankenship and R. Bentall. USGS Prof. Paper, 492, 1-383.

WHITE, D. E., HUTCHINSSON, R. A. and KEITH, T. E. C. (1988). The Geology and remarkable thermal activity of Norris Geysir Basin, Yellowstone National Park, Wyoming. USGS Prof. Paper, 1456, 1-84.

ZELENOV, K. K., 1972. Volcanoes as sources of oreforming components in sedimentary formations. Publ House Nauka, Moscow. (in Russian).