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ENERGY DEVELOPMENT PROBLEMATICS IN THE MEDITERRANEAN. THE AEOLIAN AND AEGEAN ISLANDS. THE GEOTHERMAL ENERGY CASE

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ABSTRACT

This paper aims at discussing the reasons why, despite a most favourable geothermal energy environment, the islands of the southern and southeastern Mediterranean stick to conventional energy processes and not to reclamation of alternative/renewable energy sources instead, indeed a delicate exercise.

As a result the following headings are analysed :

(i) geodynamic settings which address the Aeolian and Aegean volcanic islands arcs occurring at lithospheric plate subduction zones and, at a lesser extent though, selected nearby active rifting and graben structures, whose distinctive tectonic, magmatic and geohydrological attributes are known to host attractive hydrothermal reservoir environments,

(ii) present resource/reservoir evaluation and development status related to previous geophysical/geochemical surveys, direct drilling/testing assessments and early pilot development projects,

(iii) sensitive problem areas assumed to restrict the harnessing of proven geothermal resources in the light of the Mediterranean Insularity background and prevailing tourism oriented economics, and

(iv) overcoming past errors and present/future uncertainties by implementing relevant, challenging, geothermal energy development strategies securing feasible development and reconciling island communities, often skeptic, if not hostile with geothermal energy undertakings

In so exercising the following priority development targets are suggested, accounting for specific insular conditions.

(i) desalination from either stream condensates, high temperature flash or, preferably, low temperature evaporation cycles in order to meet island critical fresh water demands,

(ii) direct uses encompassing cooling/freezing, process heat, thermal/medicinal, space heating applications, and

(iii) power generation, once a priority objective, rated first at domestic and, optionally, at foreign requirements.

FOREWORD

While discussing with the organisers of the IGD 2002 event the author issued the following straight forward, if not provocative, statement (Ungemach, 2002).

“The Mediterranean enjoys a most attractive, proven, geothermal potential in particular (but not only) in the Aeolian and Aegean Volcanic Island Arcs, often directly assessed via drillings in Italy (Vulcano and Pantelleria) and Greece (Milos – Cyclades, Nisyros – Dodecanese). Although exploration benefitted from massive public (UN, EU, domestic) funding support no or very limited development was achieved so far.

Why ? Is there a structural impossibi-

lity, is it still worth spending public money in, beforehand, aborted projects ?

Are most of these Islands bound to stick to diesel fired turbines, tank supplied fresh water, fruit/vegetable/fish imports, to tourism as the sole development route ? To Government and European subsidies for survival ?

Are the lobbies, conservative policies, insular archaism so strong, overwhelming, that the presently bleak outlook cannot be defeated ?

Or, instead, can other alternative development scenarios be realistically contemplated ? The geothermal potential is there, the technology/knowhow exists not mentioning submarine power transmission – island to island, island to continent – practiced by the utility in the Aegean and desalinisation from steam condensates and flash/evaporation processes.

How can they be best implemented ?

We are not speaking here of Archeology"

This is what this paper is all about.

BACKGROUND AND SCOPE

The islands of the southern and southeastern Mediterranean face the paradox of utilising, in many instances, conventional energy processes whereas they enjoy among the most attractive renewable energy potential of which geothermal sources take an important share.

Such in the case of the Aeolian and Aegean volcanic island arcs of Italy and Greece which, owing to a favourable geodynamic setting –lithospheric plate subduction zones – and related tectonic, magmatic and geohydrological features are likely to host dependable hydrothermal reservoir environments.

As a matter of fact, volcanological, geophysical and geochemical exploration conducted since the investigations pioneered in the early 1950s in Vulcano (Sommaruga, 1984), in these areas as well as in nearby active rifting and graben structures, has evidenced promising shows. Those could be further validated via direct drilling asessments in the Vulcano, Pantelleria (Italy), Milos and Nisyros (Greece) island localities.

However, in spite of these promising premices, insignificant or very limited development was achieved so far.

The geothermal potential of these islands, whose main chracteristics are featured in table 1, will be analysed in the light of their remakable geodynamic settings and geothermal/magmatic attributes, and of their present resource/reservoir present exploration and developement status.

To date development of the geothermal resources has been limited to a pilot 2Mwe power plant on Milos, abandoned in the early 1990s, and to a pilot desalination unit, fed by low temperature geofluids in the Kimolos island (Cyclades).

The problem areas, deemed critical *vis-à-vis* geothermal development openings, will be reviewed with respect to

mining/geological risks. Those, examplified on several exploratory drilling ventures (Vulcano, Pantelleria, Nisyros), address the variability of reservoir properties, in both vertical and horizontal directions. It affects reservoir continuity as a result of hydrothermal alteration / self sealing, sharp lateral changes in lithology, water influx/mixing, depending chiefly on locations respective of the governing heat source and magma differentiation structure (magma chamber / caldera assembly).

exploitation risks . They relate to :

- the thermochemistry of the geothermal fluids and to dominantely scaling (carbonate, silica, heavy metal sulfide species) shortcomings and subsequent plugging of (production/injection) wells, surface facilities and, ocasionally, the reservoir proper,
- reservoir life, (re)injection. Geothermal reservoirs of the type encountered in the Aeolian and Aegean arcs are of limited areal extent conforming to a fracture dominated porosity/permeability pattern. This signature renders these reservoirs, if not adequately assessed and managed, sensitive to early pressure and temperature depletion. This bearing in mind that (re)injection of the heat depleted, waste brine is an environmental prerequesite which, if not carefully designed, could lead to production/injection well shortcircuiting and premature cooling.

environmental hazards. Besides a normal volcanic activity, island arcs are subjected to paroxismic outbursts as witnessed by, historically recorded, magmatic eruptions (Vulcano, Santorini) and phreatic explosions (Milos, Nisyros). The advent, though unpredictible yet, of such events will occur sooner or later, illustrating the seismic/volcanic risk any local development and undertaking has to cope with. The seismicity induced by the (re)injection of the waste brine may be regarded as a secondary risk, which could eventually be turned into an asset (stress release).

last, but not least, *insularity*. With the notable exception of Lesvos (North Aegean) the islands addressed to here (see characteristics in table 1), are representative of the insular context. Summing up :

(i) they are limited in size (from 20 to 300 km^2),

(ii) their topography is uneven and their esthetics outstanding,

(iii) their native population barely exceeds a few thousands inhabitants,

(iv) their economy has become wholly tourism addicted which causes the population to increase up to one order of magnitude during peak summer months. It has also profundly modified the traditional socio-economical panorama, devoted to sea and agriculture, by moving to a service dominated economy, strongly depending on imported –food, energy, fresh water, labour force- supplies, and

(v) the islanders have shown in several occasions to be skeptic if not hostile towards promoting geothermal energy. This reluctance to changes, often perceived as mere conservatism, complicates social acceptance of geothermal developments.

Locality	Country	Region	Area (km2)	Population	
				Permanent	Peak touristic
Aeolian	Italy	Sicily			
Vulcano			21	450	15,000 est.
Lipari			38	11,000	35,000 est
Pantelleria			112	7,500	n.a.
Aegean	Greece	Aegean			
Milos		Cyclades	151	4,800	15,000
Santorini		Cyclades	76	9,600	90,000
Nisyros		Dodecanese	37	950	2,000
Kos		Dodecanese	290	18,000	108,000
Lesvos		North Aegean	2133	93,000	n.a.

Table 1. Island highlights

From present resource assessments and expectations and island energy requirements the following development targets have first been selected (i) power generation, (ii) fresh water supply/ desalination, (iii) cooling/freezing, (iv) process heat, and (v) thermalism/space heating.

Their implementation will be discussed in view of reconciling development objectives with insular specificity by (i) adapting productive capacities to highly variable, season wise, loads, (ii) favouring modular design, (iii) small pilot units and demonstrative trials prior to full scale commissioning, (iv) environmental mitigation policies while accomodating seismic hazards, landscape esthetics, waste disposal, clean air and gas abatement concerns, and (v) improved communication in informing, lobbying, management and decision making thus avoiding past redhibitory mistakes.

GEODYNAMIC SETTINGS AND RESERVOIR OCCURRENCE

Most of the islands discussed here belong to the Aeolian and Aegean Island arcs which occur at lithospheric subduction zones (fig.1) where both the overridden and overriding plates consist of oceanic crust (Reeder, 1987).

In such zones magma often reaches the surface giving rise to active volcanic island arcs as is the case of the Aeolian and Aegean archipelagos.

Actually subduction zones volcanic arcs represent 62 % of the active volcanoes of the world although they supply less than 13 % of the magma erupted yearly (Reeder, 1987). If the forearc and backarc regions reflect mean heat flow values of 30 and 90 mWm^{-2} respectively (as compared to the 60 mWm^{-2} continental average) heat flows as high as 600 mWm^{-2} (i.e. tentimes the continental average) have been measured in volcanic island arcs.

More over such zones exhibit distinctive tectonic, magmatic, geological and hydrogeological features favouring the development of potentially exploitable hydrothermal reservoirs.

In fact 70 % of all electricity produced worldwide from water dominated (as opposed to dry steam) sources originates from subduction zone volcanic arcs (Reeder, 1987). They are associated with quaternary igneous systems and magma differenciation processes taking place in compressional stress environments, generating prevailing silicic calc-alkaline melts.

Reservoir occurrence is governed by fracturing and self sealing processes. Most of the geothermal reservoirs consist of host rocks fractured at depth as a result of intense magmatic, phreatomagmatic and regional tectonic stresses typical of the volcanism of these zones which often combine caldera structures, phreatic explosion craters and active faulting systems. Owing to their high source temperatures, two phase water dominated systems have a high self sealing potential in the form of mineral (silica for instance) deposition during the fluid cooling process. Self sealing is beneficial as long as it favours the formation of confining caprocks. However the risk exists of having the reservoir entirely self sealed to the point no permeable zone would no longer exist, would there not be fracturing to defeat this fatal ending.

Geothermal fluids are generally a mix resulting from the influx of meteoric, sea and connate (of marine origin) waters and of magmatic gases. A classical model of a volcanic island arc geothermal reservoir would consist of a dual aquifer system combining (i) a shallow hot water / or even saturating steam bearing horizon, with predominant meteoric recharge, and (ii) a deeper seated, hotter, hydrothermal reservoir with likely sea water (not necessarily) and connate/magmatic liquid and gas intakes. Geochemistry, chiefly isotope geochemistry, proved useful tools in discriminating water and gas origins and mixing in such reservoirs.

The Pantelleria (Sicilian channel) and Lesvos (North Aegean) islands belong to two different volcanic and tectonic settings.

Pantelleria is a volcanic island located in an active continental rift between Sicily and Tunisia.

Lesvos, located in the very North Aegean is a remnant of a tertiary volcanic island arc whose volcanism is extinct but heat flows high owing to distensional tectonics and an active graben structure.

PRESENT EXPLORATION AND DEVELOPMENT STATUS

Aeolian island arc and Pantelleria

The Aeolian island arc (fig. 2) was formed during Miocene and Pliocene, as a consequence of the fragmenting, dispersion ans subsidence of a formerly continuous lithospheric plate leading to the formation of the Western Mediterranean Basin whose peri-Tyrrhenian margin hosts active volcanoes (Stromboli, Vulcano, Lipari) (Bruno et al , 2000).

. *Vulcano*

Vulcano is an active volcanic island whose last erruption dates back to the late 1880's. Since then it has been the site of intense fumarolic and gas venting manifestations (Todesco, 1995).

The geothermal interest of the island was recognised by AGIP who, in the early 1950s, initiated exploration by drilling two shallow drill holes (Sommaruga, 1984, AGIP SpA, 1987 and Todesco, 1995) VU_1 and VU_2bis (see characteristics in table 2, and well locations in fig. 3). Well drilled in 1983/1984 turned out dry.

Besides exploratory drillholes, there are numerous shallow wells drilled for domestic use and irrigation and natural gaseous manifestations (fumaroles, gas and steam vents) which have been sampled for the purpose of geochemical and isotopic investigations (Panichi et Noto, 1992, Bolognesi et D'Amore, 1993, Cortecci et al, 2001) Studies of hydrothermal alterations and fluid inclusions have been performed to appraise rock water interactions, fluid origins and the system thermal history (Gioncada et al, 1995).

Fumarole discharge (mainly CO_2 and H_2O), which can be in excess of 1,000 t/day with temperatures ranging from 100 to 600°C (during paroxismic crises), has evidenced the presence of, shallow seated, boiling aquifers intersected actually by the early exploratory drillings.

Summing up, the foregoing enabled to assess the hydrothermal reservoir conceptual model depicted in fig. 4. According to this model hydrothermal fluids represent a mix of meteoric, connate (of marine origin) and magmatic water and gases, with superficial steam heated boiling ground water. Isotopic analyses reflect a geothermal water dilution by magmatic vapour and no direct sea water influx.

Well Name	Year	Depth (m)	Productivity	Max Temp (°C)	Observations
VU1	1952	236	2400 t/day dry steam	200	3 productive horizons (100,136,200°C)
VU2bis	1953	236	168 t/day dry steam	150	
IV1	1983/1984	2050	None	400	Well IV1 div sidetracked div. at 980 m Self sealing downhole Total circulation losses 0-900m
VP1	1984	1000	None	200	Total circulation losses 0-900 m

Table 2. Vulcano well characteristics

Lipari

In contrast with the Stromboli and Vulcano settings , active Volcanism shows are limited to hot springs and tepid fumaroles. It has been inferred volcanism is here associated to a tectonic theme under the form of a pull a part structure (Bruno et al, 2000). The volcano-tectonic faults bounding the main Lipari depressions follow the same strike as that of the tectonic structure. It is further assumed that the abscence of a caldera collapse is a consequence of the disconnection between the formation of volcano-tectonic depressions and volcanic processes.

At Lipari an integrated geophysical campaign combining microgravity, 2D geoelectrics, seismic reflection/refraction profiling surveys aimed at delineating a low enthalpy geothermal reservoir whose development could support thermal and balneological applications. Geophysiscal surveys were carried out in compliance with the following rationale.

(i) seismic profiling matches subsurface seismic discontinuities (layering, faults),
(ii) gravity constrains seismics in terms of densities vs velocities and acoustic impedances, and
(iii) geoelectric soundings pinpoint conductive anomalies.

As a result a relevant structural model could be derived over the thermal springs area which might reflect the presence of a low enthalpy geothermal reservoir within a permeable pyroclastics / lava sequence intensely tectonised via subvertical faulting likely to enhance hot fluid upwelling (Bruno et al, 2000).

Pantelleria

The island is the emerging part of a submarine dormant volcano, trending parallel to the active Sicilian channel continental rift (Chierici et al, 1995, Grassi et al, 1995, Squarci et al, 1994) (see fig. 5). It involves most of the attributes of central volcanic settings –caldeira structure, numerous hot springs, fumaroles and gas vents- with shallow water temperatures as high as 98°C (Gianelli et Grassi, 2001).

Geothermal exploration started in 1969 with the drilling of four shallow boreholes. It resumed in 1990 with the drilling of four medium depth wells (depths ranging between 180 and 400 m) located in the areas deemed the most promising. Finally two deep exploratory wells, PT1 and PT2, were drilled in 1992 and 1994 at depths of 1100 m and 1200 m respectively.

Well PT2 turned dry and cold (130°C bottomhole temperature).

Well PT1 exhibited moderate reservoir performance with a 270°C bottomhole temperature and a productive interval struck between 600 and 700 m facing a permeable brecciated horizon which, after acid stimulation, delivered a 4t/hr dry steam flowrate.

Temperatures profiles (fig. 6) monitored on six wells show a convective shift in the upper 200 meters indicative of a shallow hot water aquifer resupplied by meteorics waters.

The analysis of hydrothermal mineral and water samples collected on wells PT1 and PT2 (Fulignati et al, 1997, Gianelli et Grassi, 2001) made it possible to assess a relevant conceptual model of the hydrothermal reservoir shown in fig. 7. Accordingly the ground water circulation system involves :

(i) a shallow thermal aquifer consisting of a mixture of meteoric recharge and sea water intake,

(ii) an intermediate saline, dominantely colder, sea water influx interacting with mixing meteoric waters, and

(iii) a deeper seated system fed by upwelling geothermal fluids.

Here undoubledy, and contrary to the Vulcano model, the major inflow originates from sea water.

Aegean island arc and Lesvos

The Aegean arc is typical of a plate convergence environment as a result of the European (overriding) and African (overridden) plate subduction process taking place in the South Aegean which led to the fragmentation of the southern edge of the Eurasian lithospheric plate and to the associated structural features sketched in fig. 8. The volcanic belt extends from the gulf of Saronikos to Kos and includes the active centers of Milos, Thira (Santorini) and Nisyros (Fytikas, 1980).

Milos (Cyclades)

The island diplays the most important volcanism of the Aegean are with respect to quantity, products (calc-alkaline typical of island arc suites) and activity (Fytikas, 1989). Evidence of an intense magmatic, tectonic and geo-thermal activity is brought by surface shows such as fumaroles, hot springs, phreatic) explosion craters, hydrothermal alteration deposits numerous throughout the island and subsurface temperatures as high as 200°C monitored at 250 m depth (fig. 9).

Exploration began in the early 1970's with geophysics (geoelectric soundings, gravity survey) and the drilling of a first exploratory borehole. It was followed in 1975, 1976 by the drilling of two deep wells MZ1 and MA1 wich proved productive thus confirming the presence of a high enthalpy water dominated reservoir (Fytikas 1980 and 1989, Vrouzi, 1985). Field delineation and reservoir evaluation resumed in 1981-1982 with the drilling of three step out wells, MI-1, MI-2 and MI-3, all three productive (Cataldi et al, 1982, Vrouzi, 1985, Fytikas 1989).

Well lithological sequences and temperature profiles are depicted in fig. 10 and their main characteristics listed in table 3.

Well name	MZ1	MA1	MI-1	MI-2	MI-3
Year completed	1975	1976	1981	1981	1982
Total depth (m)	1100	1165	1100	1380	1000
Productive interval (m)	810-1100	750-1165	900-1100	940-1380	900-1000
BHT (°C)	300	250	323	282	300
BHP (Mpa)	n.a.	n.a.	11.7	11.9	n.a.
WHP (Mpa)	0.6	0.74	1.2	1.2	n.a.
Total flow (t/h)	22	51	120	50	125
Steam / water ratio (1 MPa)	0.64	0.22	0.35	0.71	0.42
Specific enthalpy (kj/kg)	2010	1170	1460	2200	1600
TDS (ppm)	$>$100,000	$>$100,000	120,000	140,000	130,000

Table 3. Milos wells summary sheet (after Cataldi et al, 1982 and Vrouzi, 1985)

Hence the features of a dependable geothermal reservoir, conforming to the conceptual model illustrated in fig. 11, could be reliably assessed. According to this model there is no occurrence of a significant, shallow seated, reservoir the main resource, most likely supplied by sea water, being hosted by fractured crystalline rocks below 700 m depth.

Projected geoelectric designs targeted

a 40MWe installed capacity (i.e. a ca 400 t/h steam rate and a dual flash condensing cycle) deemed a realistic development objective (Cataldi et al, 1982).

In 1987, after several preliminary trial and error runs, a pilot, 2MWe rated, power plant was put on line by PPC, the Greek utility and concession owner, according to the design (dual flash condensing) displayed in fig. 12, utilising MI-2 and MI-1 as producer and injector wells respectively (Delliou, 1989). The plant could not be operated continously due to severe scaling problems affecting the surface facilities (turbine, separated brine piping, injection pumps, valves etc…) reported by Delliou (1989). Scaling shortcomings have been thoroughly investigated by Andritsos et al (1989) who identified heavy metal sulfides and silicates/amorphous silica as the major scale, forming at primary flash and downstrem brine transmission stages respectiveley. Not overlooking the impact of, flashing induced, thermodynamic changes (pressure and temperature decrease) they pinpointed pH increase as the dominant factor controlling the supersaturation/precipitation processes of sensitive crystal species. Therefore they suggest careful pH control as an effective means for defeating scaling. It is the author's opinion that scale inhibition could be better and more economically mastered by enhancing precipitation under suspended particulate form by means of flash crystalliser, brine reactor clarifier and brine filtration units, a statement substantiated by the considerable experience acquired in the Imperial Valley of California (Cioppi et al, 1982).

Noteworthy is the hostility raised among the population by the environmental consequences (soil pollution) of power plant operation and, delicate euphemism, by repeated communication / public relation misunderstandings, leaving a poor image of geothermal energy whose power generation segment is henceforth black listed.

The island however has to face growing demands in fresh water supply, cooling and process heat to meet booming touristic and ore (bentonite, perlite, kaolin silica deposits) processing (drying) needs. Renewed efforts have enabled to commission a low to medium enthalpy developemnt prospect, based on the drilling / completion of ten shallow depth wells in order to drive a desalination plant of the type (MED process) implemented in the neighbouring Kimolos island. Therefore geothermal heat has a chance to reenter the island energy scene.

Thira/Santorini (Cyclades)

Thira is a mythic site, recurrently associated with the legend of the lost Atlantis, and the birthplace of one the most brilliant civilisations of the ancient Mediterranean, dating back to 2,000 BC.

It goes without saying its volcanism and seismicity are active as witnessed by numerous, historically recorded, eruptions and earthquakes. The huge caldera depression which shaped the island unique landscape was created further to the 1,500 BC great eruption. In 236 BC an earthquake broke the northern part of the island thus separating Thira from Thirassia. Later, from 197 BC till 1928, several cones emerged in the caldera, ultimately merging to form the Neakaméni islet. The last earthquake in 1956 showed devastating as to house destructions and human casualties.

Hot springs, fumaroles and high heat flows inferred from temperature gradient slimholes were shows indicative of a substantial geothermal potential (Fytikas), 1980). Further exploration combining geochemical sampling, deeper drilling (250 to 460 m) and geophysical surveys (microgravity, electrical soundings) were carried out in the mid 1980s- According to Fytikas et al (1990 they provided strong expectations on the existence of a deep (800 to 1000 m) geothermal reservoir, at source temperatures nearing 160 °C, developing in fractured and tectonised metamorphic basement rocks and recharged by uprising magmatic fluids.

Development of the resource should focus first on desalination processes to meet an urging fresh water demand, trending critical during the peak touristic months, although power generation via Organic Rankine Cycles, a speculative outcome at this stage, cannot be readily discarded.

In these respects it is worth adding that here, thanks to tactful communication, the population proves quite responsive to geothermal development prospects.

Nisyros (Dodecanese)

The island was selected in 1981 by

PPC as a priority exploration target, further to the recommendations of an EU expert team based on the following considerations (Vrouzi, 1985).

(i) a relevant –active volcanic island arc-geodynamic context supported by the positive outcome achieved at Milos in a similar setting,

(ii) associated, late quaternary, volcano-tectonic and structural features : calc-alkaline subduction zone magmatism, recent volcanic emissions of the Plinian type, a typical caldera summital structure, post caldera events including historical phreatomagmatic explosions (1872-1873), fumaroles and hot springs on the outer flanks reservoir, at temperatures in excess of 200°C relatively shallow depth, and

(iii) the possibility of exporting the locally produced geothermal electricity surplus to the nearby islands of Kos, Kalymnos and, eventually, Rhodos via sub-marine cable transmission technology in a shallow sea environment,as already practiced in the area by the utility.

Two exploratory wells (see locations in fig. 13) were drilled in the early 1980s whose main characteristics are summarised in table 4 (Koutroupis, 1989).

Well Name	N-1	N-2
Year completed	1982	1983
Total depth (m)	1,816	1,547
Productive interval (s) (m)	360-695 1,420-1,816	1,000-1,547
BHT (°C)	350	350
WHT (°C)	n.a.	178
WHP (bars)	n.a.	7.6
Total flow (t/h)	13(*)	69
Steam water ration	0.8(*)	0.5
Specific enthalpy (kj/kg)	2,350(*)	1,520
Non condensable gascontent (% wt)	n.a.	5
TDS (ppm)	150,000(*)	60,000

(*) superficial reservoir

Table 4. Nisyros wells summary sheet

This drilling venture examplifies incidentally the strong variability in both reservoir occurrence and performance , illustrated in fig. 14 temperature logs, typical of the Mediterranean island arc geothermal reservoir environments noticed already in the Aeolian arc. On well N-1 only did the shallow seated reservoir exhibit productive, limited though, capacities. On the contrary well N-2, drilled on kilometer apart, evidenced a deeper seated resource worth developing owing to a net 3 MWe power output as compared to a hardly 1 MWe counterpart on well N-1.

In depth analysis of geochemical data and phreatic explosion crater morphology enabled Marini et al (1992) and Chiodini et al (1992) to produce a pertinent conceptual model of the Nisyros geothermics portrayed in fig. 14.

At present the N-1 and N-2 wells have been abandoned and cemented. No alternative development schemes have shaped yet. The island community, whose population has decreased by one half in the past decades, is still waiting the advent of innovative and challenging development opportunities.

Kos (Dodecanese)

Kos is located at the extreme edge of the Aegean volcanic island arc. The western part of the island exhibits a dist-inctive caldera structure, known as Volca-nia, which could favour the development of a hydrothermal convective system, a thesis advocated by Bardinzeff et al (1989).

No geothermal investigations have been commissioned so far. However, the prosperous economics of the island, whose population regularly increases, boosted by an explosive touristic income, might deserve reconsidering the geothermal case in reclaming known/expected low to medium enthalpy sources and subsequent direct use applications.

Lesvos (North Aegean)

Eventhough Lesvos belonged once to a volcanic island arc, its tertiary origin no longer supplies active magmatic/volcanic processes manifest as in the Cyclades and Dodecanese. Neither do its graben tectonics shape as favourably as their eatsward Turkish replica. However, the island is an active seismic area (1867 earthquake) as a result of its distensive tectonics yielding higher than normal heat flows. It enjoys numerous hot springs and abundant water intakes which render the island an attractive prospect addressing low to medium enthalpy sources.

The thermal areas of Polichnitos, Petra/Argenos and Kalloni/Stipsi, located near the main, NE trending, graben structure have long been recognised as priority exploration/development targets (Fytikas, 1980, Vrouzi, 1985).

Neotectonic investigations have aslo identified the Mythilene area as a reliable candidate (Dotsika et al, 1995).

Recently, completion of a deep drilling wildcat well has confirmed these expectations by hitting a 98°C / 150 m^3/h hot water aquifer at 1,000 m depth.

The island which ambitions sharing traditionally rooted, agriculture oriented economics, with well balanced touristic / residential trends deserves in deed pertinent geothermal, direct use oriented, undertakings.

DEVELOPMENT PROBLEMATICS

The foregoing highlighted the technical and non technical obstacles contraining the development of island geothermal reservoirs.

Technical obstacles. They address the following risks and hazards.

Exploration/exploitation risks

With the exception of the hundred per cent drilling success ratio recorded in Milos most other island drilling ventures exhibited erratic reservoir and well performances (vulcano, Pantelleria and, at a lesser extent though, Nisyros) as a result of the sharp changes noticed, both vertically and horizontally, in reservoir properties.

It has been shown that fracturing and self sealing, typical of volcanic islland arc hydrothermal environments, are, alongside magmatism and tectonics, the key processes governing the formation of high enthalpy water dominated reservoirs. Self sealing is regarded an asset as it secures the confinement of the reservoir. It can also be detrimental would it seal the reservoir to the point no permeability would remain whatsoever. So fracturing is needed to counter this adverse trend which requires active magmatic and regional tectonic stresses which actually favour the ascent of deep hot magmatic fluids.

In no way can fracture induced permeability/porosity patterns be assumed continuous in such complex volcano-tectonic systems and caldera edifices.

However exploration in the Aeolian and Aegean is not starting from scratch. Previously reported investigations enabled to assess generic reservoir models providing geothermal explorationists with relevant guidelines, thus reducing the geological risk inherent to any mining operation.

Scaling and injection are among the most critical exploitation problem areas. Heavy metal sulfide and silica scale dramatically impacted the operation of the Milos pilot geoelectric plant, causing its shut down further to repeated unsuccessful trials and remedial failures. Although scaling affected here the surface facilities and brine transmission line, the risk of injection well impairment and reservoir damage should no be overlooked in future plant and brine handling designs. In this respect inspiration could be sought from the brine processing concepts successfully implemented in the geothermal fields of Southern California (Cioppi et al, 1982) whose fluids exhibit similar, if not more hostile, thermochemical properties. These processes favour the precipitation of sensitives scale species under particulate form which, after due filtering, achieve the injection of a crystal free brine.

Injection of the heat depleted brine in the source reservoir, indeed an environmental (waste disposal) prerequesite, is another matter of concern. The fractured nature of the reservoir may provoke well shortcircuiting and subsequent, earlier than anticipated, cooling of production wells and shortening of reservoir life. Therefore, careful design of production vs injection well spacings via reservoir simulation codes, supported by long duration well testing and fluid tracing studies, is required to thoroughly assess reservoir behaviour and match fluid preferential flow paths. This, bearing in mind that limited (inland) reservoir sizes (Vulcano, Nisyros), added to rapid lithological and structural changes, are likely to reduce the mining of the heat in place.

Environmental hazards

It goes without saying the islands of the Aelian, Sicilian channel and Aegean face high, structural, volcanic and seismic risks inherent to their active volcano-tectonic settings. As a matter of fact the late major eruptive / seismic outbursts date back to 1888/1891 – Vulcano – and 1956 – Santorini. Both these islands are now equipped with observatories monitoring seismo-volcanic activity and signalling precusory shows of paroxysmic events with a view to ultimately / tentatively secure eruption and eathquake prediction.

Whatever these risks neither have they opposed to, long established, island community settlements nor dissuaded touristic crowds. Given this context, obviously should any geothermal development prospect be designed and implemented in compliance with paraseismic volcanic building/monitoring safety standards widely applied worldwide, particularily in geothermal power plant design in similar geodynamic environments in Japan, the Philippines and Indonesia among others. Hence these hazards can be mastered in the framework of a topical risk management rationale.

Injection of cooled geothermal brines has been reported to cause microseismic activity and thermal stresses. These secondary impacts could actually prove beneficial by (i) favouring the release of long accumulated stresses wich otherwise might have generated devastating earthquakes, and (ii) upgrading, thanks to thermally induced fracturing, well injectivity.

Non technical obstacles

Most investigated islands share common features, the so called insularity, characterised by (i) limited acreages, (ii) small communities, (iii) uneven topography often associated with oustanding sceneries, (iv) tourism addicted economics substitued for traditionally oriented agriculture/sea activities, and (v) moderate (when not hostile) social acceptance of geothermal development schemes.

As earlier discussed reduced island acreages are limiting factors to reservoir development, an issue manageable regarding native populations seldomly exceeding a few hundred to several thousand inhabitants. This **irrespective** of peak summer tourist crowds rising the population by one order of magnitude, if not more, and energy, freshwater, food, manpower demands accordingly, wich poses a crucial base to peak load adjustment problem.

As regards island steep reliefs and related landscape esthetics, conventional plant, hot water piping and power transmission line concepts should be readily discarded and alternative designs be promoted instead. This arises critical environmental and social acceptance considerations. Geothermal energy, especially power generation, development is assimilated to industrial undertakings, indeed an image conflicting with Mediterranean settlements, whose origins are lost in the mists of times and dedicated to agriculture, fishing, sailing and trade before the overwhelming touristic boom took over.

This attitude, shared occasionally by temporary residents, is often regarded by outsiders as merely conservative if not archaic. Both attitudes are in fact caricatural.

It should be stressed here that the mining industry in Milos is an important part of the island economics with ore quarries producting yearly ca 1,000,000 t of Bentonite, 100,000 t of perlite and 10,000 t of silica and kaolin. Obsidian was also extracted in ancient times in the Aeolian.

Natural sites need to be protected which implies that geothermal projects must fit into the landscape, hopefully better than recent residences and shops, built according to somewhat anarchic urban planning criteria. Pollution control requires that sound and safe waste disposal and gas abatement procedures be implemented to prevent from adding brines and gases to those of the existing hot springs, fumaroles and gas vents.

In these respects, reconciling geothermal developments with nature and public acceptance is examplified by Japan where most geoelectric power plants were built in National parks and seismic areas, subject to stringent environmental regulations.

Clearly the foregoing deserve innovative challenging development strategies.

FUTURE PROSPECTS

Owing to insularity geothermal development strategies are strongly site specific, to the stage each island can be regarded as a case study of its own. Nevertheless there are a number of common features, as to identified geoelectric and geoheat sources, candidate conversion/recovery processes and eligible domestic uses, allowing to draw general guidelines, prior to reviewing, island wise, the resource to demand adequacy.

Development targets

Power generation

High and medium enthalpy, either dry steam or hot pressurised water, deposits are available almost everywhere. Power generation addresses the following conversion cycles (Ungemach, 1987) (i) direct steam expansion, (ii) back pressure, (iii) single/dual flash condensing, and (iv) binary, Organic Rankine Cycles (ORC) the latter recommended within the 120 to 180° C temperature range.

Noteworthy is that electricity could be effectively used for powering desalination and freezing/cooling processes.

Desalination

It is deemed the most urgent need as a result of the endemic shortage of fresh water, critrical during the touristic season. The unit domestic and touristic demands are estimated at 200 and 300 l/day respectively. Fresh water could be recovered from steam condensates whenever available and more generally, from sea water or geothermal brines by means of thermal processes among which Multiple Stage Flash (MSF) and Multiple Effect Distillation (MED) stand as the best candidates although Mechanical Vapour Compression (MVC) should not be excluded in case excess electric power be available on the site.

Desalting sea or brackish water (World Wide Water, 1999) involves its boiling/evaporation in a still, thus releasing steam which condensed will form pure water. Stacking stills (i.e. staging) increases process efficiency provided each sucessive still is at lower pressure so that boiling occurs at sucessively lower temperatures. This is the basis for the MED process wich requires a constant input of heat supply during boiling. The MSF process consists of keeping the boiling water under pressure until released into a vacuum vessel, causing the water to flash into steam. Summing up, connecting multiple effects or stages at successively lower pressures is the concept behind the MSF and MED processes whose diagrams are sketched in fig. 16 and 17 respectively.

In the MVC process the heat for evaporating is supplied by vapour compression instead of direct heat exchange from the boiler steam. The process utilises most often electrically driven vapour compressors. Process performances figures are displayed in table 5

Process	Power Requirements Kwh/t		Steam Requirements kgs/kgd		Output Distillate kgd/kgs	
	Min	Max	Min	Max	Min	Max
MSF-OT	2.38	3.17	0.13	0.5	2	8
MSF-BR	2.64	3.96	0.08	0.25	4	12
MED	0.75	1.75	0.1	1	1	10
MED-TC	0.75	1.5	0.07	0.33	3	15
MVC	8.5	12	0.03	0.05	20	40

Symbols and subscripts

MSF : Multistage flash - OT : Once Through - BR : Brine Recirculation
MED : Multiple Effect Distillate – TC : Thermocompression
MVC : Mechanical Vapour Compression
s = steam, d=distillate

Table 5 : Performances of selected desalination processes

MSF plants are of large scale (capacity up to 50,000 m3/day) and operate at high temperatures (90-110°C) downstream from the brine heater which renders them sensitive to corrosion and scaling. They are also more energy demanding and are therefore often used in combination with power generation.

MED units operate at lower temperatures, thus minimizing corrosion and scaling. They can be designed for capacities up to 20,000 m3/day and can achieve distillate/steam ratios as high as 15 MED should appeal to geothermal developers since it is less energy consuming, requires lower process temperatures and uses the geothermal brine as a single heating and feeding source.

The MED pilot plant serviced at Kimolos, which supplies daily 77 m^3 (i.e. ca 50 % of the domestic fresh water demand) from a 50 m^3/h – 61°C geothermal brine, should prove rewarding for the whole area.

Direct uses

They include various applications such as (i) cooling/freezing, best achieved via heat pump and absorption systems (using Lithium bromide or Ammonia as refrigerants), (ii) process heat for agricultural (vegetable, fruit) and industrial (ore processing) drying, and (iii) miscellaneous - space heating, balneology, aquaculture - uses.

Project review

This represents by all means a highly tentative, if not speculative, exercise leading to the following expectations.

Vulcano

Insofar as they prove sustainable, deliverabilities of shallow dry steam wells UV1 (100t/h) and UV2bis (7t/h) should achieve nominal geopower capacities amounting to ca 5,000 and 500 kWe respectively. The latter figure meets the power requirements of the island population. The total capacity could supply the peak summer demand. An alternative scenario could consist of connecting Vulcano to the nearby Lipari island via a submarine power transmission line.

Recovery of steam condensates would allow to supply the local fresh water demand and, incidentally, to bypass waste reinjection.

In conclusion the domestic power and fresh water needs could be realistically fulfilled.

Lipari

Exploration should resume by drilling two exploratory boreholes in order to check the conclusions of an integrated geophysical survey, carried out over the thermal spring area, which inferred the presence of a low enthalpy reservoir. It should also enable to reprocess the former geophysical data.

The development objective is at present limited to low grade heat addressing space heating/cooling, thermal and medicinal uses with desalination added as an option.

Pantelleria

The island is a puzzling dilemma. In spite of numerous surface naifestations, deep drilling exploration stood below expectations. Nonetheless a dry steam source was evidenced that could ease accessing to a dependable hight enthalpy reservoir, in which case power generation could be contemplated to meet a local demand estimated at ca 5 MWe.

There are elsewhere abundant low to medium enthalpy sources, suggesting to select desalination as a main development objective, bearing in mind that a 90 °C – 200 m^3/h resource could sustain a ca 700 m^3/day fresh water output securing half of domestic requirements , presently supplied by tankers.

Other direct use oriented applications are considered in the waiting of future drilling/testing assessments.

Milos

Milos has been shown to host the highest geopower potentiel recorded to date in the whole Aelian/Aegean region, estimated at 15 MWe, based on existing well deliverabilities. Whatever the presently bleak outlook and low profile, power generation ought to be given, one day or another, a chance to prove technically feasible, economically viable, environmentally safe and be harnessed accordingly.

Priority is given to desalination prospects. A recently commissioned project, targeted at a 100 m^3/h – 90° C brine production from shallow wells, should supply a 240 m3/day fresh water output, covering 25 % of the island domestic demand.

The locally active mining industry should welcome the contribution of geothermal low enthalpy sources in driving the drying segment of the ore processing line.

Thira/Santorini

Desalination is given the highest priority. It should be achieved by drilling wells of the type designed in the Milos scheme. They would allow to delineate the candidate shallow reservoir, thus complementing the data collected from early slinehole drilling reconnaissance.

At this stage, a 150 m^3/h – 90° C well deliverability, meeting ca 20 % of the fresh water needs of the island community, seems a realistic objective.

The existence of a, deeper seated, medium enthalpy reservoir remains hypothetical. Possibly could, in the future, exploratory wells be drilled and, if successful, lead ultimately to power generation using ORC technology.

Nisyros

Early development expectations, targeted at power generation capacities as high as 10 to 20 MWe, are now abandoned in spite of an encouraging deep drilling exploration outcome.

Prospects are at standby stage. It would be worth resuming geothermal "expro" by commissioning a small size, incentive, project to somehow counter the adverse island desertification trend.

In this perspective, the drilling of a well aimed at a combined power generation/desalination plant rated at 500 kWe/250 m^3/day, capable of supplying community power/fresh water needs could provide the necessary stimulus.

Kos

Long considered a second ranked geothermal objective, the island did not attract gethermal explorationists. However, the western located, Volcania caldera setting, assumed to host a hydrothermal reservoir, deserves further geophysical/ gechemical investigations and exploratotry drilling in order to thoroughly assess the local resource potentialities.

Lesvos

By far the most large and populated island, Lesvos hosts significant, proven and inferred, low to medium enthalpy resources as a result of graben active/ distensive tectonics and abundant water recharge.

Several exploration/development projects, presently at commissioning stage, should lead to, presumably reliable, direct use oriented applications.

Although premature at this stage, in the waiting of the actual temperature status, power generation (ORC technology) from medium enthalpy sources, could be foreseen to meet the demands of island communities either directly or via connection to te grid.

Implementation

Project evaluation and commissioning should account for the following considerations.

(i) a significant geothermal energy potentiel has been identified bu insignificant commercial development has been noticed yet,

(ii) power generation from proven high enthalpy sources, once thought the most promising development route, has been abandoned,

(iii) desalination instead raises a growing interest from several island communities,

(iv) toursim brought a massive income which, conversely, added to already sensitive energy/fresh water supply problems, not mentioning the consequences of, season wise, unbalanced socio-economics,

(v) the island communities, in most instances, proved reluctant, when not hostile, to geothermal energy, particularily power generation, development prospects.

Given this context geothermal energy has to bridge a credibility gap addressing decision makers, fund backers and island communities. This clearly does not reduce to a simple image problem.

As a result, a unified approach to common problems, benefitting from the expertise and knowhow available throughout the geothermal community is recommended on both bureaucratic and practical informal.

It could take the form of an informed task force involving an expert core group, representatives of island communities and stakeholders among other parties in the framework of an ad-hoc Mediteranean rewenable (geothermal) energy (sub) programme. Whatever bureaucratic this suggestion may be it coud ease accessing to decisions and funding and, last but not least, formalise communication between concerned actors and partners.

Practically, with a view to reduce entrepreneurial risks and gain credibility, the project evaluation and commissioning process should (i) focus on argumented exploration targets, (ii) stick to small pilot exploitation units and convincing demonstrative trials prior to full scale commitments, (iii) favour modular designs compatible with local environmental requirements, (iv) secure project feasibility and related technical/managerial skills, and (v) improve communication with whoever is concerned.

CONCLUSIONS

Exploration, carried out since the early 1950s (Aeolian) and 1970s (Aegean), confirmed the high geothermal potential of the Aeolian Sicilian channel and Aegean regions expected from their distinctive geodynamic settings (active volcanic island arcs, rift and tectonics) and hydrothermal environments.

So far no tangible development followed the discovery of high enthalpy sources, eligible to power generation, in the Vulcano, Pantelleria, Milos and Nisyros islands, although the area at large faces severe energy/fresh water supply problems particularily during peak touristic months.

This paradox has been analysed in the light of the following limiting factors and barriers.

(i) exploration/mining risks, sensitive in the Aeolian and Pantelleria,
(ii) exploitation risks and environmental hazards, examplified in Milos, and
(iii) insularity, a generic label addressing the island physical and socio-economic features alongside the skeptic, when not hostile, attitude of the community towards geothermal, chiefly power generation, development opportunities.

Given the foregoing the following development guidelines are suggested.

(i) allocate to desalination, using preferably the attractive MED process, the highest priority in meeting in the critical fresh water demand of most island communities,
(ii) promote low to medium enthalpy sources and related cooling/freezing, process heat, thermal/medicinal, space heating direct uses,
(iii) give power generation, in spite of its presently bleak outlook, a second chance,
(iv) focus on argumented exploration targets, small exploitation units prior to large scale commitments, modular, environmentally compatible, designs, and reliable technical/managerial skills, and
(v) last but not least, improve communication with concerned island communities.

These guidelines should bridge the credibility gap geothermal energy is facing in the Mediterranean area and, ultimately, secure the development targets proposed in the, island wise, project review.

So, everything considered, geothermal energy has a good chance.

ACKNOWLEDGEMENTS

Never could have this paper been written without the contributions of Maria Papachristou, Adele Manzella and Cecilia Giussani who provided the author with invaluable documentation and advice. Would also the organisers of the "IGD 2002 Greece" meetings, particularily Kiril Popovski, be thanked for their patience in waiting for this paper.

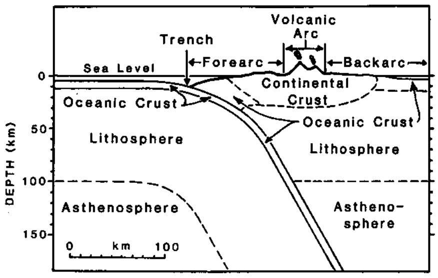

Figure 1. Generalized tectonic cross-section model for a subduction zone (Reeder, 1987)

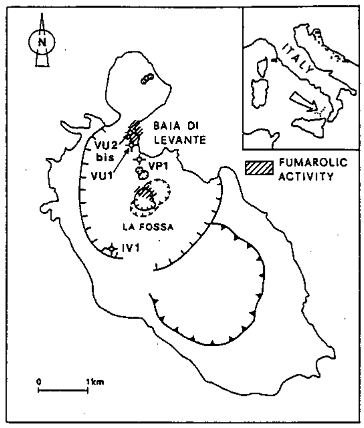

Figure 3. The island of Vulcano (Aeolian Islands). The location of the geothermal wells is indicated along with the areas characterized by fumarolic activity. (Todesco, 1995)

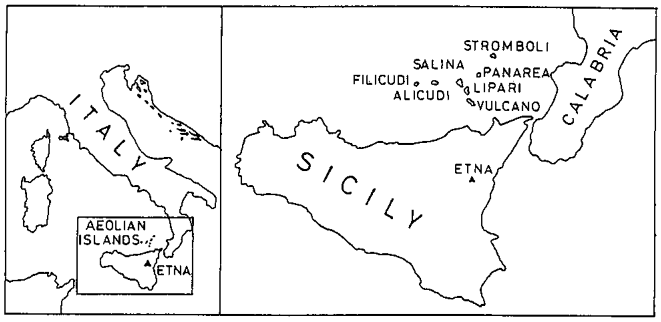

Fig.2. Location map of Vulcano and Aegean islands

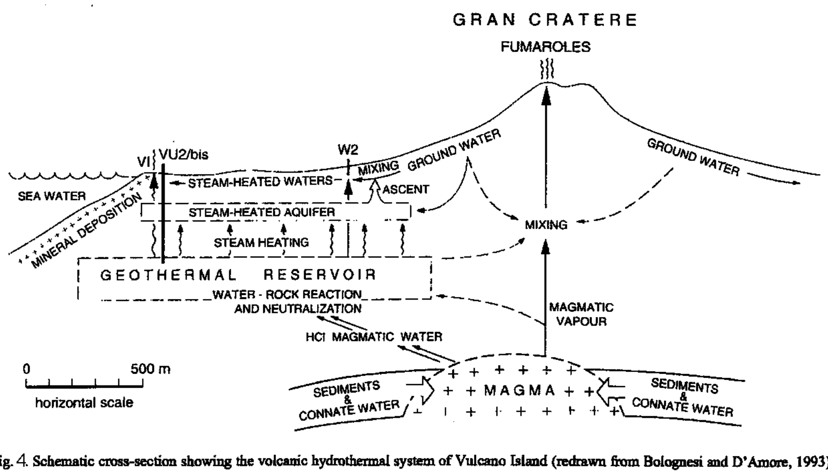

Fig. 4. Schematic cross-section showing the volcanic hydrothermal system of Vulcano Island (redrawn from Bolognesi and D'Amore, 1993).

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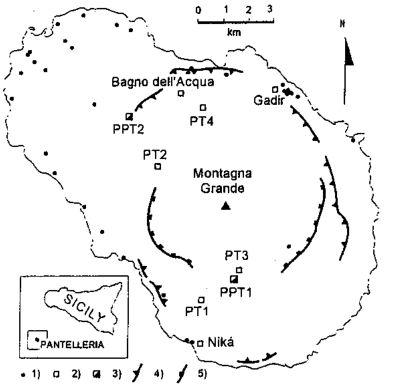

Fig. 5. Schematic map of Pantelleria. (1) Water wells and springs; (2) shallow exploratory wells; (3) deep geothermal wells; (4) young nested caldera rim; (5) older caldera rim. After Grassi et al. (1995).

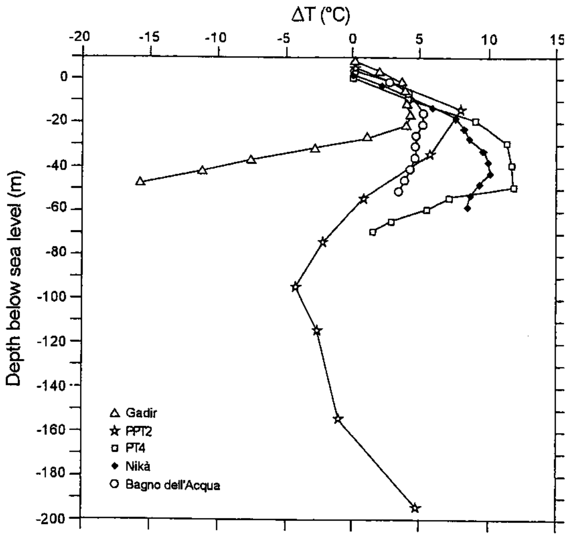

Fig. 6. Temperature profiles of Pantelleria water wells and springs (Gianelli et Grassi, 2001)

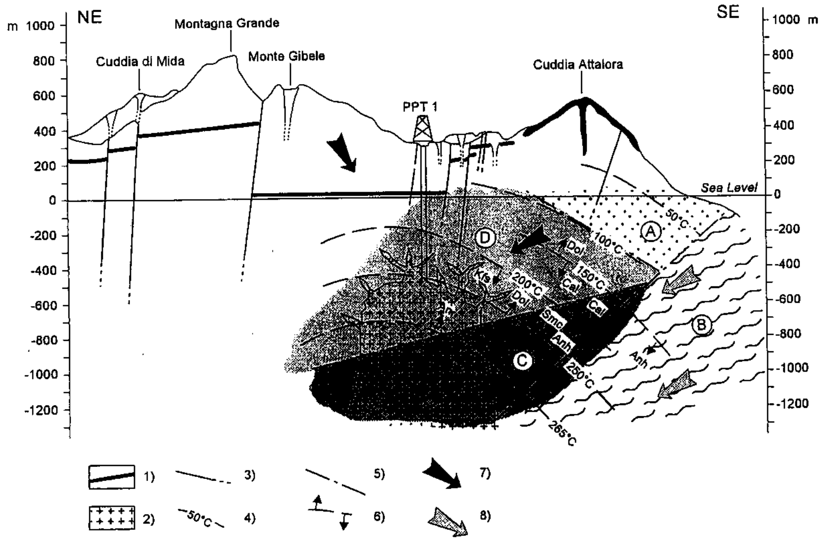

Fig.7 . Conceptual model of the geothermal system of Pantelleria (geological scheme and profile after Chierici et al., 1995a): (1) recent pyroclastic rocks; (2) trachyte; (3) faults; (4) isotherms, (5) boundaries between zones characterised by fluids of diverse origin; zone A = strong prevalence of meteoric waters, zone B = sea water recharge, zone C = marine waters and volcanic gas, zone D = marine and meteoric waters, with volcanic gas; (6) theoretical appearance (inward) or disappearance (upward) of key alteration minerals: Dol = dolomite; Cal = calcite; Anh = anhydrite; Kfs = K-feldspar; Smc = smectite; (7) direction of meteoric recharge; (8) direction of marine recharge.

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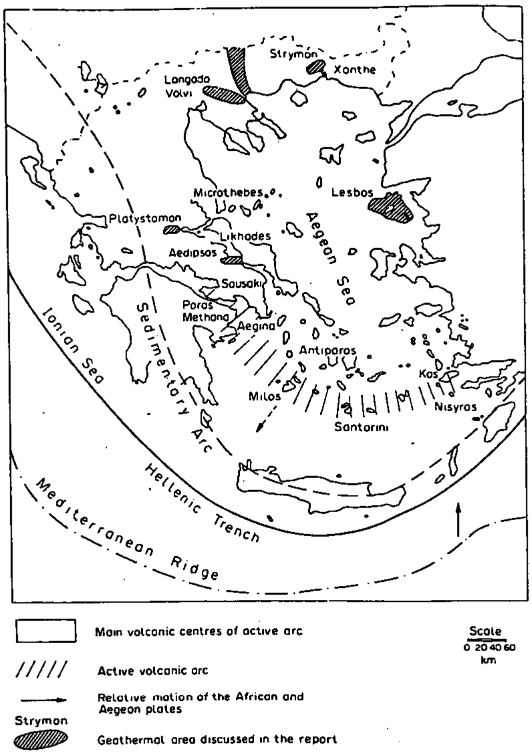

Fig. 8. Structural sketch map of Greece. (Fytikas, 1980)

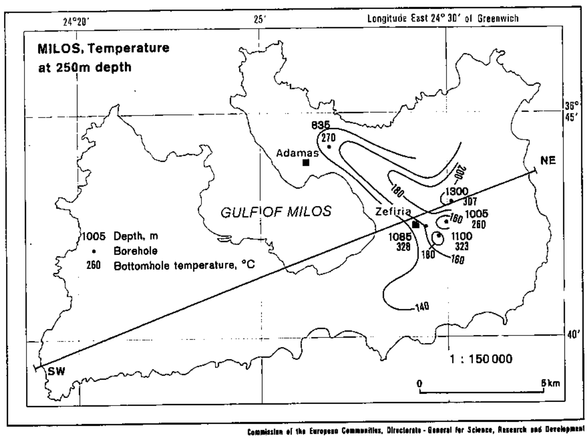

Fig. 9. Temperatures at 250 m. Milos island.

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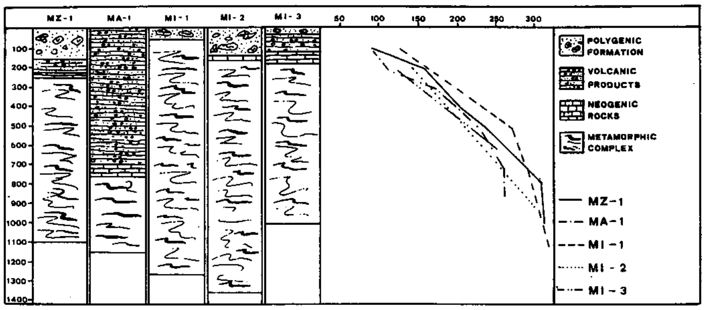

Fig.10- Lithological sequence and virgin temperatures (Cataldi et al, 1982)

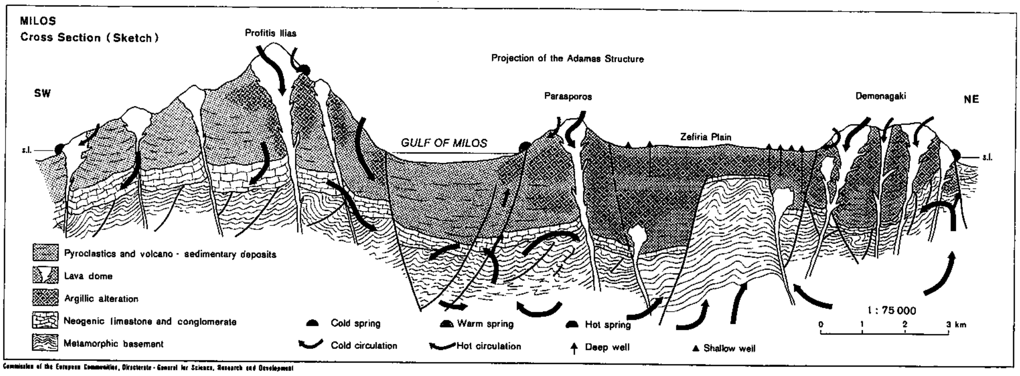

Fig. 11. Geothermal cross-section (sketch) of Milos island. (European Geothermal Atlas)

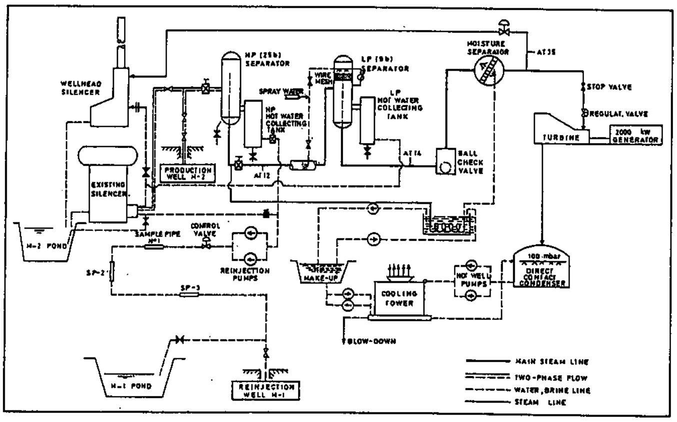

FIGURE 12 MILOS, 2 MW GEOTHERMAL POWER PLANT (existing). (Delliou, 1989)

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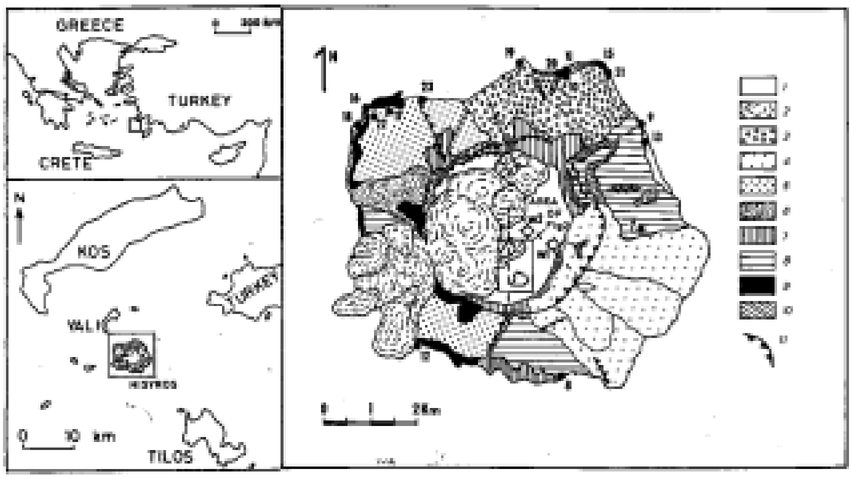

Fig.13. Location maps and simplified geological map of Nisyros Island (modified from Di Paola, 1974). 1=alluvial deposits; 2=dacitic-rhyodacitic domes and flows; 3=dacitic pumice falls; 4=perlitic rhyodacitic lava flows; 5=acid tephra; 6=andesitic lava flows and dykes; 7=dacitic lava flows and dykes; 8=andesitic tephra; 9=subaerial basalts; 10=basaltic pillow lavas and hyaloclastites; 11=major structural discontinuities. Sampled springs and shallow boreholes are indicated by filled circles and squares. W1 and W2 represent the deep geothermal wells Nisyros-1 and Nisyros-2.
(Marini et al, 1993)

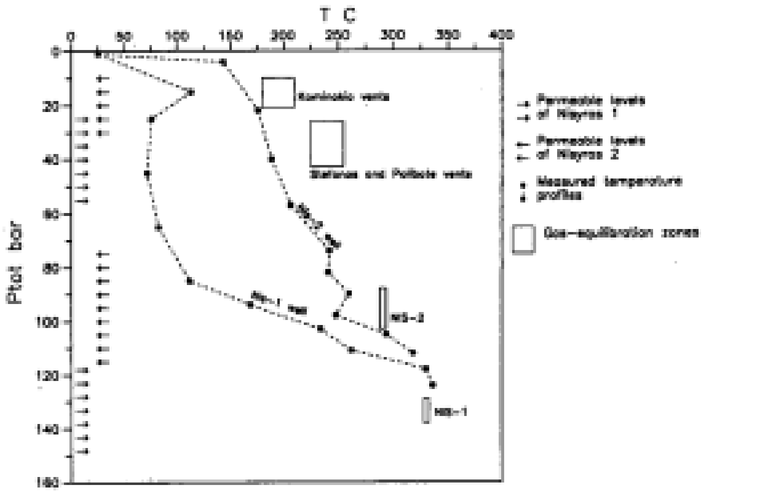

Fig.14. Comparison of the equilibrium *P,T* conditions evaluated for the fumaroles and geothermal wells with *P,T* profile of the deep geothermal wells, and with the location of the two permeable zones met during drilling.
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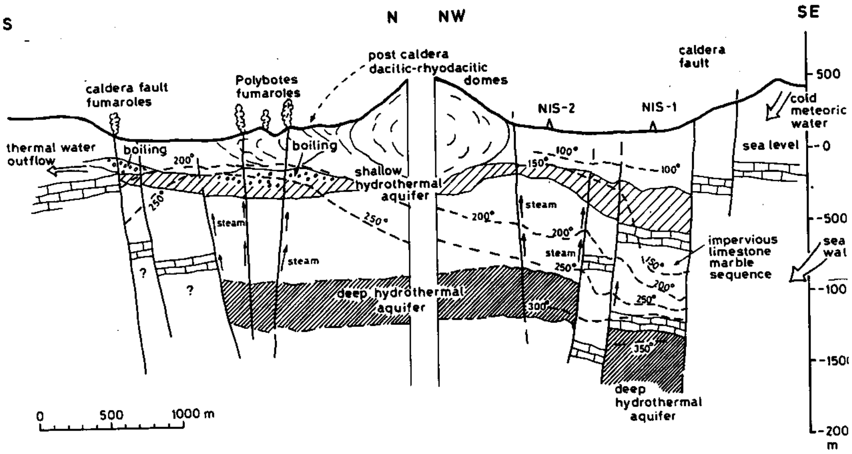

Fig. 15. Schematic cross-sections through Nisyros hydrothermal system. (Chiodini et al, 1993)

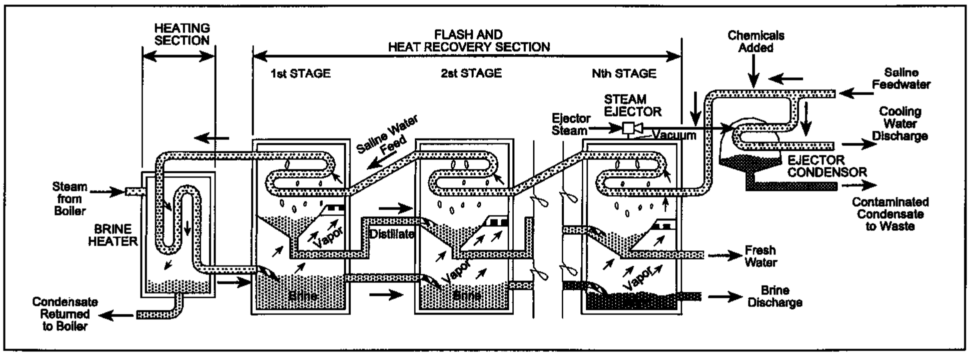

Fig. 16. Multi-Stage Flash Process (Int. Desalination Ass.)

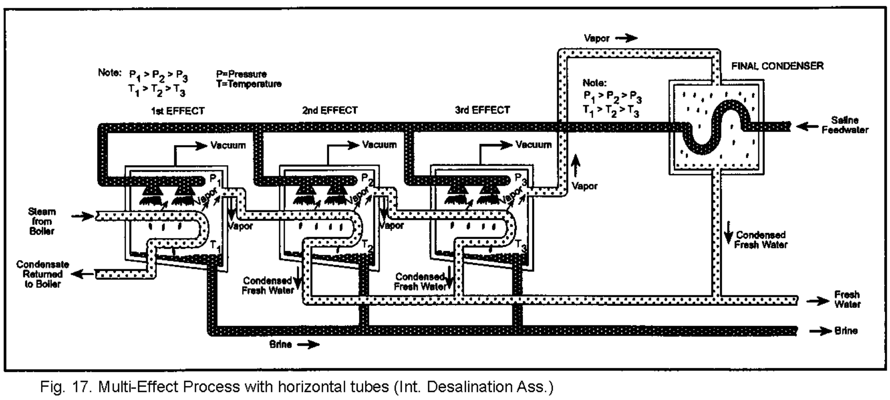

Fig. 17. Multi-Effect Process with horizontal tubes (Int. Desalination Ass.)

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