VIII.

HYDROGEOLOGY, FLUID GEOCHEMISTRY AND THERMALISM

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INTRODUCTION

The Alban Hills hydrogeological system covers an area of about 1500 Km^2. By convention, the boundary of this system is marked by flow measuring stations located at the edge of the drainage network, which flows radially away from the volcanic complex (fig. VIII.1).

In the western sector, close to the coast, the considered area includes outcrops of the Plio-Pleistocene sedimentary deposits which underlie the Alban volcanic rocks.

The average elevation of the Alban system is 151 m, while 57% of the area is included within the 0-100 m elevation range (fig. VIII.2). The highest elevation (956 m) occurs at Maschio delle Faete, a mountain located at the centre of the entire system.

The morphology is typical of a strato-volcano, with a higher and more recent central edifice surrounded by a peripheral belt predominantly consisting of older pyroclastic deposits.

Phreatomagmatic explosions caused the formation of numerous depressions; some of these eventually became deep lacustrine basins, such as Alban, Nemi and Giulianello lakes.

The slopes are cut by a complex hydrographic network that descends radially from the extracaldera area toward the periphery of the system. These streams converge with the Sacco, Aniene and Tiber rivers in the eastern, northern and north-western sectors of the Alban area, respectively. In the south-eastern and southern sectors the Alban hydrographic network discharges to the Pontinia Plain, while in the western sector it flows into the stretch of coastline between the Anzio and Tiber outlets.

HYDROGEOLOGICAL COMPLEXES

The lithostratigraphic characteristics inferred both from deep wells located at the boundary of the Alban Hills area and from the analysis of the sedimentary "ejecta" (Funiciello & Parotto, 1978; Amato & Valensise, 1986), allow the identification of the following hydrogeological complexes (figg. VIII.3, VIII.4):

a) *Calcareous-siliceous-marly basal complex*

The Meso-Cenozoic complex, ranging from middle to upper Lias, is cha-

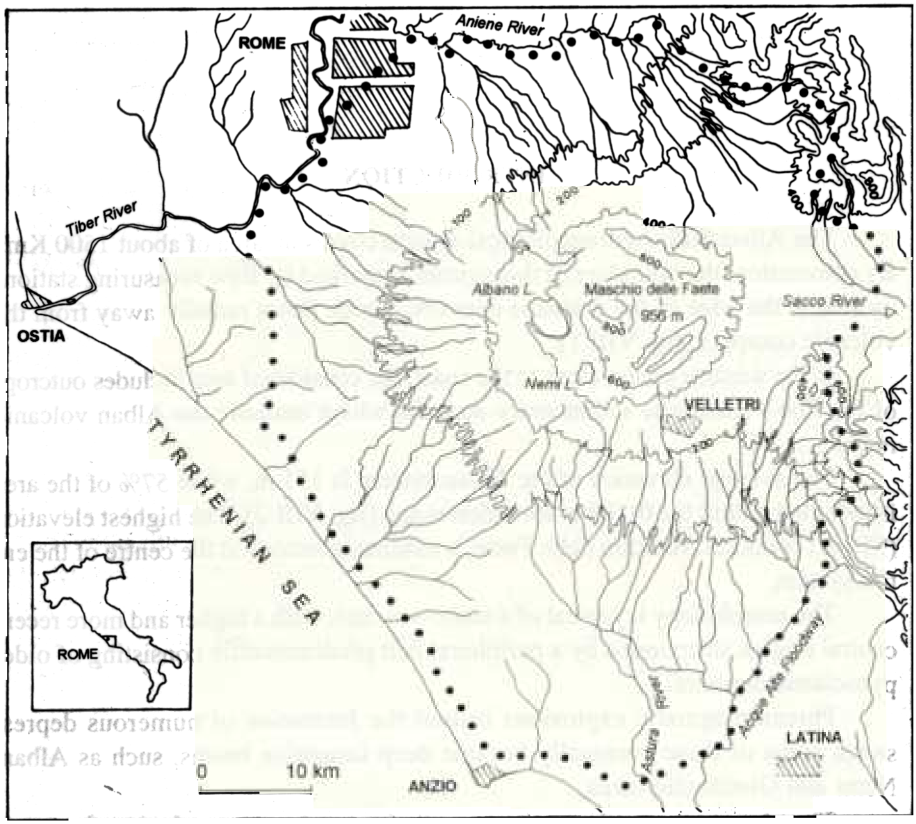

Fig. VIII.1 - Location map showing the Alban volcano and surrounding area.

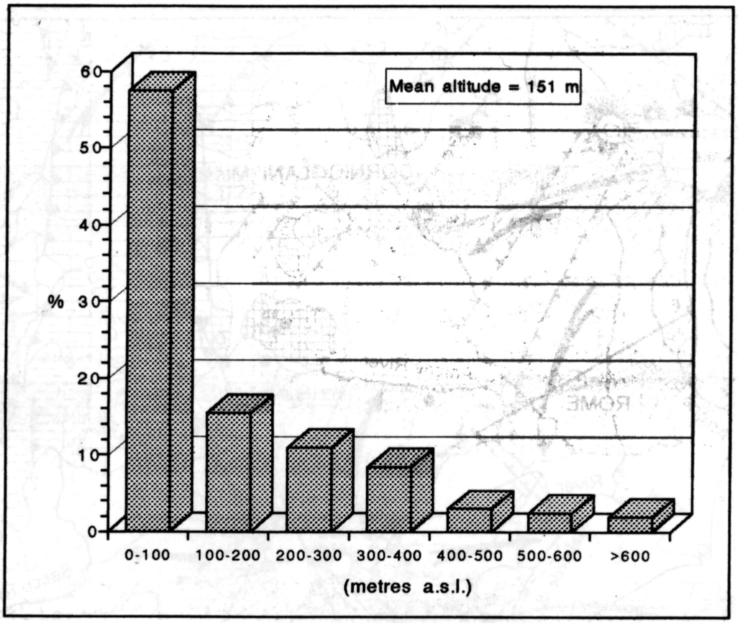

Fig. VIII.2 - Elevation zones of the Alban volcano area (1500 Km^2)

racterised by transition facies of the Sabina Series. The complex was tectonically deformed during the upper Miocene and dislocated into blocks by Plio-Quaternary extensional tectonic. The lithologically heterogeneous units of the series constitute a multilayered aquifer of intensely fractured limestones and dolomites interbedded with confining clay layers. It is likely that the lower Mesozoic sequence (neritic karst facies) which overlies the Sabina Series represents the most productive aquifer of the complex.

b) *Clayey-marly complex*

These Plio-Pleistocene sedimentary deposits transgressively cover the basal complex, increasing in thickness up to several hundred meters towards the Tyrrhenian sea. It is likely that the general low permeability of this complex creates a flow boundary when the cover deposits are continuous and of considerable thickness. Unfortunately, however, knowledge is limited on the lateral continuity and thickness of the clayey-marly complex in the Alban Hills area (fig. VIII.4).

c) *Alban Hills volcanic complex*

Predominately explosive activity caused the formation of a typical strato-volcano depositional pattern. Long quiescent periods and the activity of

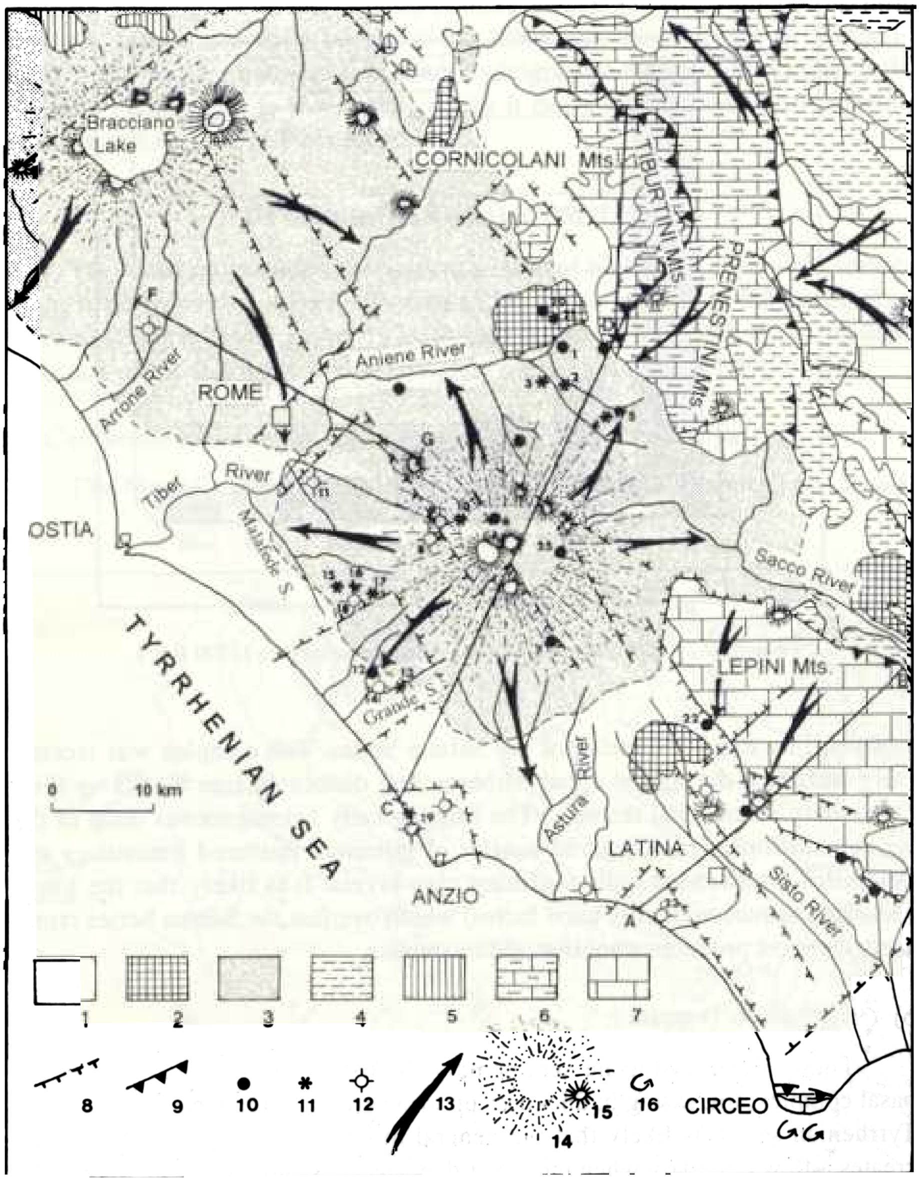

Fig. VIII.3 - Schematic map showing the hydrogeology of western central Italy (from Boni, Bono, Capelli, D'amore & Lombardi, 1981b): 1) Plio-Quaternary continental and marine deposits. 2) Travertines; 3) Volcanic deposits. 4) Argillaceous-arenaceous flysch deposits (MIOCENE); 5) Marly-calcareous-siliceous flysch of Tolfa area (UPPER CRETACEOUS-OLIGOCENE); 6) Calcareous-siliceous-marly Sabina series (MIDDLE LIAS-OLIGOCENE); 7) Carbonate shelf Laziale-Abruzzese series (UPPER TRIAS-CRETACEOUS); 8) Normal fault; 9) Main reverse fault and overthrust; 10) Spring; 11) Gas leak; 12) Well; 13) Ground water flow direction; 14) Volcanic edifice and (15) main vent pipes; 16) Submarine spring.

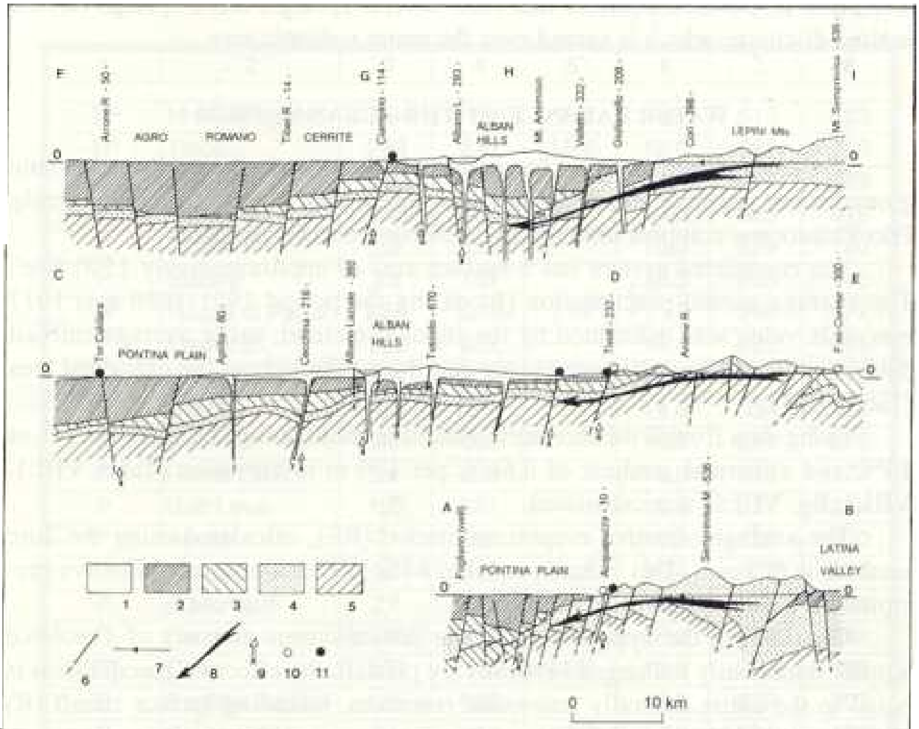

Fig. VIII.4 - Hydrogeological setting of Alban Volcano and the Pontina Plain area: Simplified cross-sections (from: Boni, Bono, Capelli, D'amore & Lombardi, 1981b): 1) Alban volcano deposits; 2) Argillaceous and marly deposits (Aquiclude); 3) Multilayer aquifer (Sabina series); 4) Karts aquifer (Laziale-abruzzese series); 5) Dolomitic regional subtratum (UPPER TRIAS); 6) Normal fault; 7) Piezometric surface in the regional kart aquifers; 8) Ground water flow direction in karstic aquifers; 9) Gas flow paths; 10) Karstic spring; 11) Spring water associated to gas phase (CO_2), characterized by moderate thermal anomaly or high salinity.

peripheral vents complicate the morphology and sedimentology, in terms of both time-variable paleohydrology and the deposition of units with different textural facies (Funiciello & Parotto, 1978; De Rita *et al.*, 1988).

Travertine horizons of hydrothermal origin, as well as alluvial deposits, are found within the volcanic sequence. Two large travertine outcrops are located at the boundary of the examined area (Tivoli; Cisterna) to the north-east and the south of the central edifice.

The significant lateral and vertical variability in lithotypes which characterises the Alban Hills area stratigraphy results in a wide range of permeability values of the complex. Morphological, structural and sedimentary conditions define a multilayered aquifer, with radial flow from the extracaldera sector towards the edifice boundary. The heterogeneity of the lithotypes has caused the formation of perched aquifers that feed several springs; these springs have a limited discharge which is spread over the entire volcanic area.

WATER BALANCE OF THE ALBAN SYSTEM

A water balance analysis focused on evaluating the naturally renewable ground water resource and defining the hydrodynamic role of the clayey-marly Plio-Pleistocene complex underlying the Alban volcanic deposits.

The considered system has a surface area of approximatively 1500 Km^2. The average annual precipitation (P) during the period 1921-1989 was 1017 mm; this value was calculated by the topoyet method, using average rainfall data from 25 rain gage stations evenly distributed throughout the examined area (Tab. VIII.1).

Using data from 7 thermometric stations a mean annual temperature (T) of 15°C and a thermal gradient of 0.66°C per 100 m of elevation (Tabb. VIII.1, VIII.2, fig. VIII.5) was calculated.

The average effective evapotranspiration (RE), calculated using the Turc method, is 652 mm. This value is equal to 64% of P, consequently effective precipitation (EP) is equal to 365 mm/y.

Considering the hypothesis that the Alban system consists of a isolated aquifer dominantly recharged vertically by rainfall, the effective precipitation is equal to the entire naturally renewable resources, including surface runoff (R) and effective infiltration (EI).

An estimation of R and EI, based on data from areas with similar lithology (north-western Latium), gives values of 8% and 28% of P, respectively, for an annual precipitation of about 1020 mm.

An average effective infiltration rate of 285 mm/y has been calculated for the Alban Hills area, being equal to about $427.5 \cdot 10^6$ m^3/y of the naturally renewable ground water resources. This value corresponds to 13.6 m^3/sec and unit flow rate of 9 $l/s \cdot Km^2$.

An understanding of the boundary conditions of the Alban hydrogeological system comes from the analysis of runoff (via the perennial hydrographic network) at the outlets of the area, using monthly discharge measurements from October 1978 to September 1979 and again from April 1981 to March 1982.

From October 1978 to September 1979 (Boni *et al.*, 1980) the average amount of the perennial-stream base flow in the system reached the value of 15.9 m^3/s, corresponding to an annual precipitation of 1105 mm. The effective infiltration of 335 mm/y, and the unit flow rate of 11 l/sKm^2, result from the field data of the average base flow.

The effective evapotranspiration, related to a 15.2°C average annual temperature, is equal to 704 mm/y. Consequently, the effective precipitation is 400 mm/y and, by difference with EI, the calculated surface runoff is close to 65 mm/y, equal to 6% of annual precipitation.

TABLE VIII.1 - Rainfall recording stations

1	2	3	4	5	6	7	8
TP	M.Guadagnolo	1204	1196	9,0	8,2	**513**	**683**
TP	Tivoli	238	831	15,6	15,0	**621**	**210**
P	Zagarolo	318	1284		14,4	**695**	**589**
P	Colonna	343	944		14,3	**625**	**319**
P	Pantano	53	815		16,3	**629**	**186**
P	Salone	23	751		16,5	**605**	**146**
TP	Rocca di Papa	685	1275	11,6	11,9	**598**	**677**
P	Frasacati	322	867		14,4	**606**	**261**
TP	Velletri	352	1232	15,2	14,2	**714**	**518**
P	Albano	384	1011		14,0	**633**	**378**
P	C.leone	56	956		16,3	**681**	**275**
P	Roma EUR	24	806		16,5	**629**	**177**
P	C.di Leva	102	851		16,0	**637**	**214**
P	Aprilia	71	836		16,2	**636**	**200**
TP	Ardea	37	843	14,8	16,4	**607**	**236**
P	B.Montello	27	881		16,5	**660**	**221**
P	Cisterna	81(100)	970		16,0	**678**	**292**
TP	Cori	397	1158	16,2	13,9	**733**	**425**
P	Paglian Casale	116	982		15,9	**679**	**303**
P	Roma UCM	51	719	16,0	16,3	**581**	**138**
P	Valmontone	306	1200		14,5	**685**	**515**
P	Paliano	450	1063		13,5	**629**	**434**
TP	Segni	666	1308	12,4	12,0	**628**	**680**
P	Anagni	470	1141		13,4	**640**	**501**
P	Sgurgola	386	1346		14,0	**688**	**658**

1 - Recording equipment: P (rain gauge) TP (thermometer and rain gauge)
2 - Recording station
3 - Station altitude (m)
4 - Mean precipitation (mm/y)
5 - Mean temperature (°C)
6 - Mean temperature (°C) "inferred data"
7 - Evapotranspiration (mm/y)
8 - Effective precipitation (mm/y)

The high rainfall during the examined period suggests that the average discharge related to the base flow includes surface runoff contributions. The effective infiltration rate of 335 mm/y is thus considered to be an over-estimation.

From April 1981 to March 1982 (Bono *et al.*, 1983), the average discharge

TABLE VIII.2 - Air temperature recording stations (fig. VIII.5)

n°	Station	Altitude (m)	Temperature (°C)
1	Roma U.C.M.	51	16.0
2	Roma S. I.	55	15.6
3	Tivoli	238	15.6
4	Velletri	352	15.2
5	Segni	666	12.4
6	Rocca di Papa	685	11.6
7	M. Guadagnolo	1204	9.0

of the system's perennial streams was about 10 m^3/s, corresponding to an annual precipitation of 784 mm. The effective infiltration of 208 mm/y, and a unit flow rate of 6.6 l/s·Km^2, is based on the average base flow field data.

The effective evapotranspiration, related to an average annual temperature

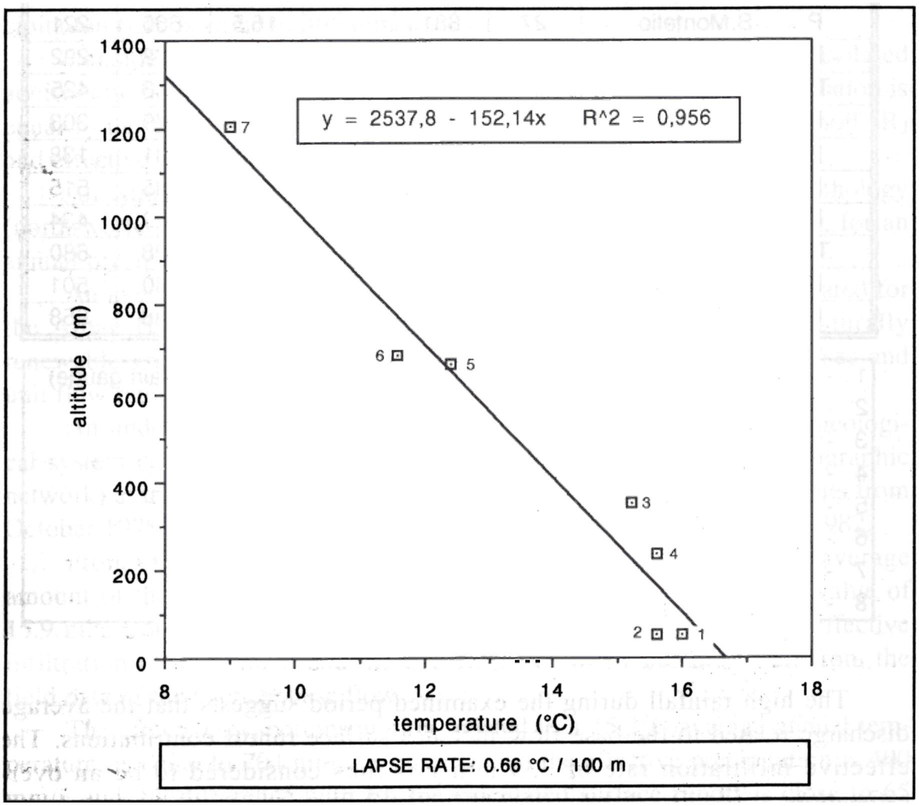

Fig. VIII.5 - Thermal gradient in the Alban Hills area of 15.4°C, is equal to 580 mm/y; as a consequence the effective precipitation is equal to 204 mm/y. This value is considered comparable to the effective infiltration rate, thus surface runoff is negligible related to an annual precipitation of 784 mm. Hydrographic separation analysis of the Treia river (north-western Latium) supports this assumption when similar annual precipitation values are used.

The water balance analysis indicates:

a) a significant congruence between EI values for the average (1921-1989), the 1978-1979 p.p. and 1981-1982 p.p. periods (using precipitation values of 1017 mm, 1105 mm and 784 mm, respectively).

b) a noteworthy similarity between PE and IE values in the particularly dry period 1981-1982 p.p., which had negligible surface runoff contributions.

c) that the unit infiltration values is between 6.6 and 11 $l/s \cdot Km^2$ (using precipitations values of 784 and 1105 mm/y, respectively.

The results of the water balance analysis indicate that the Alban hydrostructure can be considered as a hydraulically isolated system, predominantly (or exclusively) vertically recharged by precipitation.

Although possible, water exchange between the Alban hydrostructure and peripheral karstic aquifers is thought to be insignificant and quantitatively unappreciable when it is calculated using the water balance method.

This conclusion allows us to hypothesise a substantial continuity of the Plio-Pleistocene clayey-marly deposits that cover the Alban Hills area and, moreover, to attribute to these deposits a boundary effect between the volcanic aquifer and the potentially warm basal aquifer (karst reservoirs). The low thermal activity of the basal aquifer within the volcanic rocks, as well as the occurrence of several cold gas-leaks at the boundary of the Alban system, support this hypothesis.

HYDROGEOLOGICAL SETTING

The local hydrogeological setting indicates the existence of two main aquifers, one located in the Alban Hills volcanic complex and the other in the calcareous-siliceous-marly basal complex.

The volcanic aquifer is vertically recharged by local infiltration, as indicated by the water balance analysis. The hydrostructure is particularly complicated at a detail scale. On the whole, flow occurs in layered aquifer horizons that coalesce in the peripheral areas of the Alban volcano.

These considerations are supported by the flow pattern of the system. In fact, springs are dominantly located along the stream beds that cut into volcano slopes, supplying over 90% of the entire discharge (fig. VIII.6). Some groups of springs, located to the north of the central edifice at the border of the lava flows, are located mainly along the periphery of the volcanic system.

The alban spring waters, partly used during the Roman Age, now feed the Appio-Alessandrino aqueduct (A.C.E.A.) at a flow rate of 1.2 m^3/s (Acqua Vergine, Acqua Felice).

In particular, the Alban and Nemi lacustrine basins and the Squarciarelli springs are fed from a perched aquifer which extends to the interior of the caldera belt, with flow directions converging toward the western boundary of the central edifice.

GROUNDWATER FLOW IN THE VOLCANIC AQUIFER

In the Alban Hills volcanic aquifer two hydrogeological units, each having a different flow pattern, are identified (fig. VIII.7):

a) the intracaldera unit

b) the extracaldera unit

The intracaldera unit is bordered by the Tuscolano-Artemisio belt and is 75 km^2 wide.Of this area, 50% consists of hydromagmatic deposits and characterized by limited infiltration and low storage capacity.

The hydromagmatic sequence, acting as a relative aquiclude, overlies the piroclastic deposits and the lava flows of the central activity of the Campi di Annibale. About 25% of the intracaldera area consist of alluvial deposits of reworked pyroclastic rocks which overlie the hydromagmatic unit .

The intracaldera unit contains a perched aquifer, to which several springs can be referred. Most of the springs are located at an elevation between 375 and 540 m along the western border of the caldera (Squarciarelli, Alban and Nemi lakes) and their mean discharge is about 0,5 m^3/s. The Doganella spring is located on the eastern caldera border at 350 m a.s.l.; its water is characterized by low TDS value (120 mg/l) as compared to the average salinity values of the Alban system (400-500 mg/l) (Tab. VIII.3).

The extracaldera unit is characterized by radial ground water flow through a multilayered, and still undifferentiated, aquifer. The aquifer mainly feeds the perennial stream flow of the drainage network.

The average ground water discharge of the Alban system is approximatively 14 m^3/s (Tab. VIII.3). More than one third of the total discharge is concentrated within the streams of the southern sector. In this area the groundwater peizometric surface is few metres above sea level. The streams receive ground water contributions through seapage as they cut through the Quaternary fluvial-marshy and marine deposits (Aprilia Plain and Pontina Plain). The Fosso Grande stream and the drainage system of the Astura River have highest seapage rate. Towards the sea, the volcanic aquifer recharges the sandy coastal deposits (sand dunes).

In the northen sector, ground water discharge of about 3 m^3/s directly feeds the Aniene River tributaries between 80 and 50 m.a.s.l. The Acqua Vergine spring (Salone) is located in this area, having a mean discharge of 1 m^3/s and an

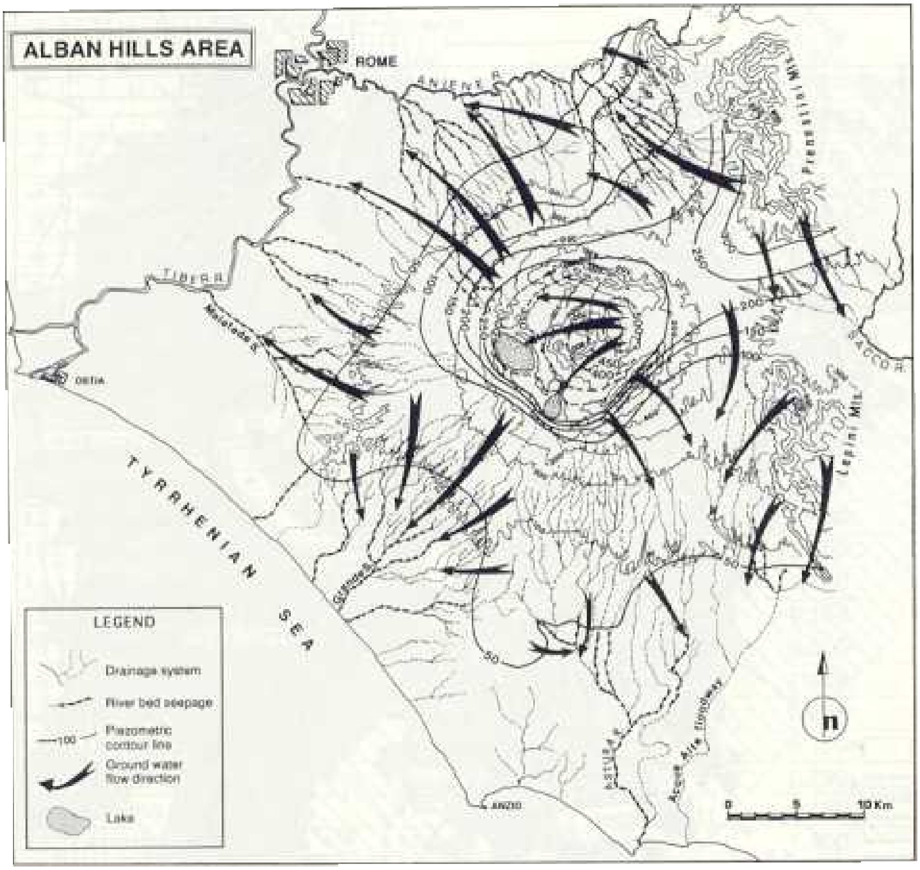

Fig. VIII.6 - Piezometric contour lines and ground water flow directions.

elevation of 20 m a.s.l.

In general the major seapage discharge is observed where the streams cut into the "Tuscolano-Artemisio Pyroclastic Flow II" (DE RITA *et al.*, 1988). This formation, together with the "Tuscolano-Artemisio Pyroclastic Flow I", forms the oldest permeable volcanic unit that outcrops in the studied area. The basal aquifer of the Alban system occurs in these units, with lower peizometric surfaces in the Aniene and Tiber River basins.

The Acqua Felice spring (100 m a.s.l.) is located along the border of a wide lava flow outcropping to the north of the central volcanic edifice. The high elevation of this spring suggests that it is fed by a perched aquifer in the lava deposits, sustained by the impervious sequence of the "Tuscolano-Artemisio Pyroclastic Flow IV".

Groundwater discharge towards the western sector (Tiber River) appears

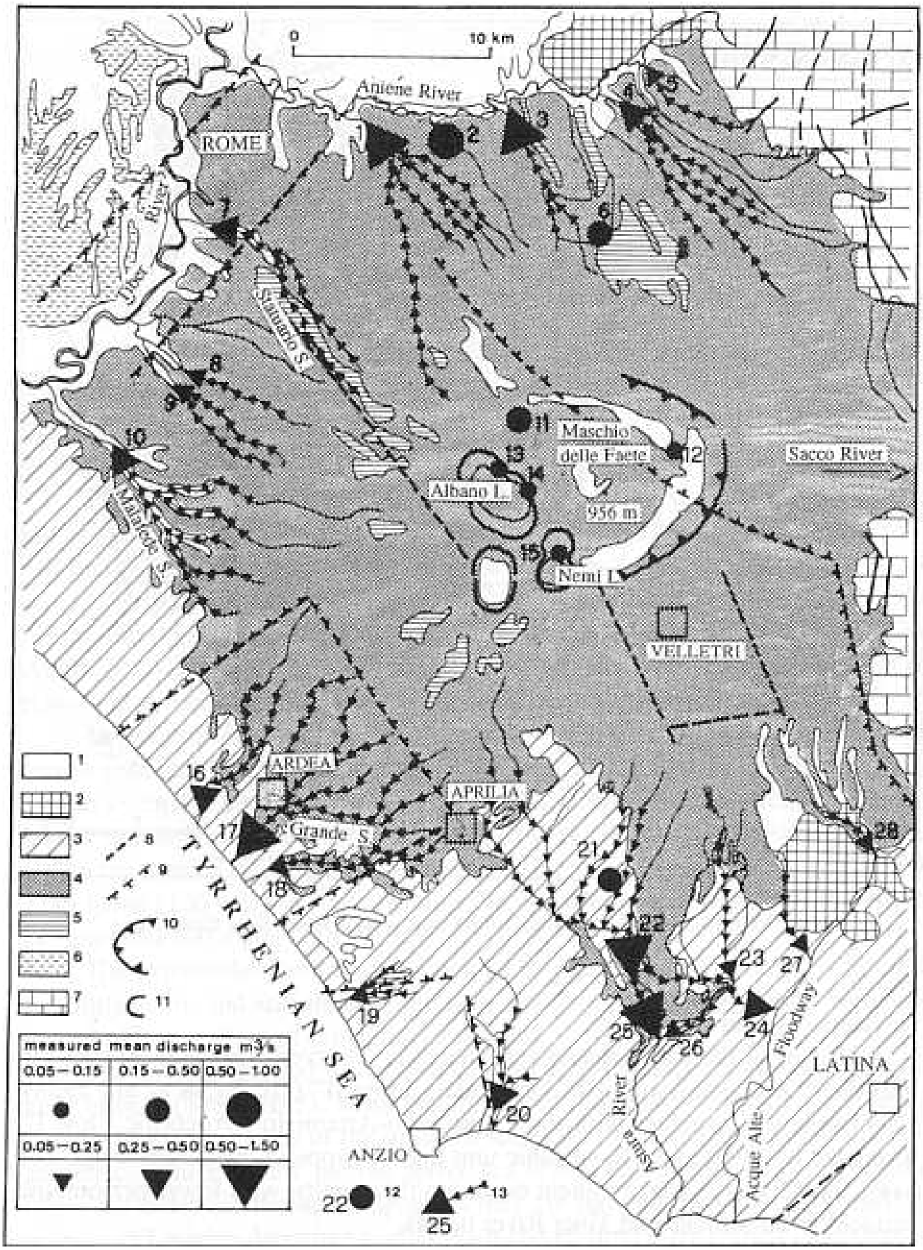

Fig. VIII.7 - Hydrogeological system of the Alban volcano (from: BONI, BONO & CAPELLI, 1988): 1) Alluvial deposits (PLEISTOCENE-OLOCENE); 2) Travertine (QUATERNARY); 3) Sands and fluvio-lacustrine deposits (QUATERNARY); 4) Volcanic deposits (PLEISTOCENE); 5) Lava flows; 6) Heterogeneous complex of clastic deposits (PLEISTOCENE); 7) Karstic complex (MESOZOIC); 8) Fault; 9) Normal fault; 10) Border of the caldera; 11) Crater; 12) Spring; 13) Stream seapage.

TABLE VIII.3 - Stream flow discharge (base flow) and main chemical - physical water characteristics (from: Boni, Bono & Capelli, 1988).

N°	Name	Altitude (m)	T (°C)	T.D.S. (mg\l)	Mean discharge (mc/sec)
1	Tor Sapienza	20	13.5	550	0.870
2	Salone	24	14.5	540	1.000
3	Osa	30	14.1	40	0.750
4	Val Freghizia	48	14.2	620	0.450
5	San Vittorino	48	14.7	450	0.200
6	Acqua Felice	100	14.0	350	0.230
7	Statuario	15	17.1	700	0.410
8	Acquacetosa	32	15.9	570	0.065
9	Vallerano	40	15.3	370	0.100
10	Malafede	14	15.6	500	0.450
11	Squarciarelli	375	12.0	500	0.170
12	Doganella	530	16.1	120	0.100
13	Acqua di San Leonardo	330			0.050
14	Albalonga	540	12.0	320	0.050
15	Le Facciate I e II	395	13.0	510	0.150
16	Torto	2	17.6	600	0.300
17	Grande	6	17.7	510	1.100
18	Moletta	5	16.6	460	0.250
19	Cavallo morto	3	16.6	520	0.100
20	Mola	2	16.4	410	0.290
21	Carano	47	19.0	400	0.160
22	Astura I	37	16.1	240	1.400
23	Matto	31	20.8	360	0.200
24	Allacciante Astura	27	16.8	340	0.400
25	Astura II	9	16.7	400	0.600
26	Colle Rufo	16	17.9	470	0.090
27	Cisterna	32	19.3	600	0.220
28	Teppia	45	14.8	330	0.100

to be minor since stream flow seapage is limited to only 1 m^3/s between 10 and 50 m a.s.l. Ground water contributions are related mainly to Fosso Malafede and Fosso Statuario. The recharge area is too large to justify the limited discharge from this sector of the system, therefore unconsidered ground water losses are hypothesised in the Alban Hills aquifer towards the Tiber River. The extreme urbanization of the area does not allow for reliable experimental controls.

No significant present-day springs are known in the eastern sector of the Alban Hills area where surface drainage converges toward the Sacco River.

WATER CHEMISTRY

Since 1971, water from the main springs in the Alban Hills have been widely studied from a chemical and isotopic point of view (Barbieri *et al.*, 1987; Boni *et al.*, 1979, 1980, 1981a-b; Bono, 1981; Cortecci *et al.*, 1980; Dall'Aglio *et al.*, 1988, Duchi *et al.*, 1991; Giggenbach *et al.*, 1988; Governa *et al.*, 1989; Lombardi, 1975; Enel, 1987; Zuppi *et al.*, 1974).

In the present paper only a short review of the chemical results obtained during the period of 1977-1979 (Boni *et al.*, 1979-80) will be presented so that the fluid circulation in the studied region can be described; to enhance these earlier results, the papers cited above have been considered for the discussion.

The study was performed, with the financial support of C.N.R. (Progetto Finalizzato Energia Geotermica, PFE-1), to study the hydrogeological setting and geothermal potential of the area. To this end several springs, water pools and boreholes were chosen as follows:

— clear pure members were selected after a preliminary geochemical and hydrogeolgical survey of each possible aquifer: the volcanic main aquifers and the buried basal aquifers (karst reservoirs);

— waters with chemical and thermal anomalies have been studied to define possible upwellings of deep origin (geothermal) fluids. It is worth noting that most of the sampled waters are enriched in a gas phase (mainly CO_2) and that some have been collected directly over gas vents.

The locations of the studied springs are shown in fig.VIII.3. The analytical data are plotted in a Piper diagram and in a Na-K-Mg triangular plot (fig. VIII.8-VIII.9).

The results, showing a wide range in the water chemistry, clearly show the complexity of fluids circulation in the Alban Region. In fact, the waters can be classified as follows:

a - alkaline earth bicarbonate type, and alkaline earth and alkaline bicarbonate type (usually with salinity below 1.2 g/l);
b - alkaline earth bicarbonate and sulphate type;
c - alkaline chloride type;
d - acid sulphate type.

a) The alkaline earth bicarbonate and the alkaline earth and alkaline bicarbonate types represent respectively:

– bicarbonate waters circulating at relatively shallow depth in the Mesozoic limestones (Ninfa, n.22; Acqua Bullente I and II, n.4-5). Ninfa, a spring located on Lepini Mt., has water characterised by a very low salinity (<0.5 g/l) and can be considered to represent a pristine example of a relatively shallow and rapid transport in a karstic aquifer. The others, located on the north-eastern flank of the Alban Hills, have waters with slightly higher salinity values (in the range 0.5-1.2 g/l) due to the mixing of karstic water with deep seated gas (mainly CO_2) that rose along faults;

– waters linked to shallow and faster circulation in vulcanic rocks, such as Doganella (25), S.Maria dell'Orto (7) and P. Co.Mi.RO. (18), which have a very low salinity values (<0.5 g/l). The other waters of this group (Squarciarelli, 6; S.M. delle Mole, 8; Acqua S. Pietro, 9; Laurentina, 11; Lav. Ardea, 12;. Collina Mare, 13; Acqua S. Stefano, 14), located in the volcanic edifice area and in its western margin, have slightly higher salinity values (0.5-1.2 g/l). Their salinity values, as well as their relative enrichment in sodium and potassium (and silica), can be explained by the leaching of vulcanic rocks near the surface under disequilibrium conditions. A gas phase (mostly CO_2 of deep origin) is often present

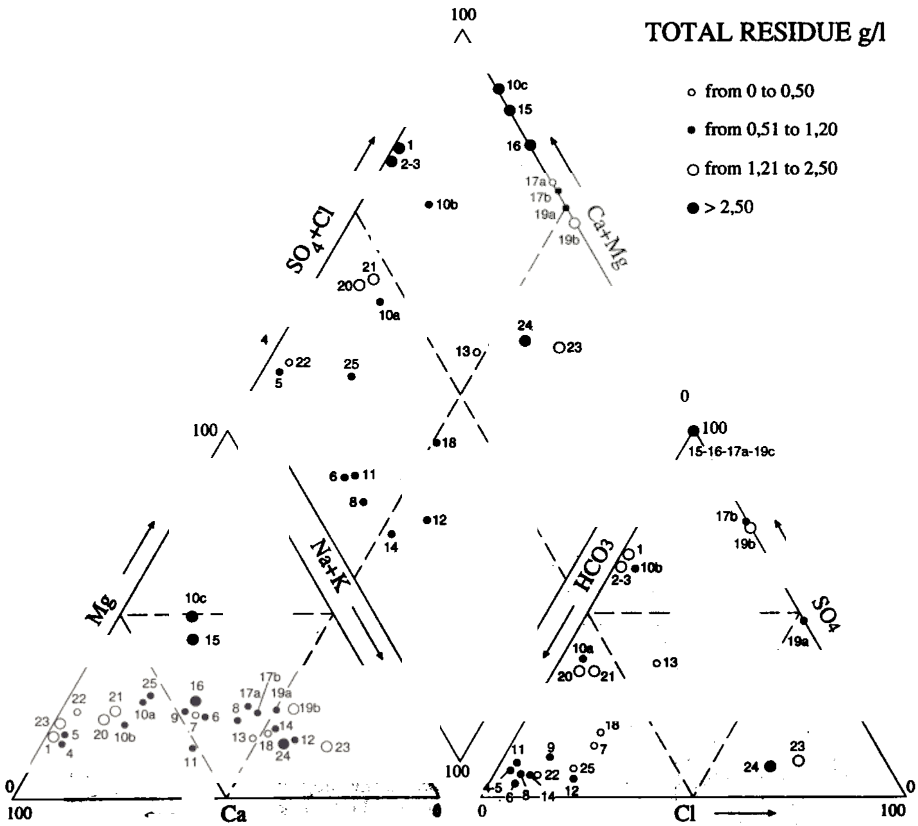

Fig. VIII.8 - Piper diagram representation of the analytical data showing the wide variation in water chamistry. The studied waters can be classified as follow: alkaline earth-bicarbonate type (shallower karstic aquifers) and alkaline earth and alkaline bicarbonate type (gas rich waters from the shallow aquifers in the volcanic complex); alkaline earth-bicarbonate and sulphate type (deeper karstic aquifers); alkaline chloride type (water diluted at depth by trapped sea water); acid sulphate type (due to the interaction between shallow waters and gas emanations)

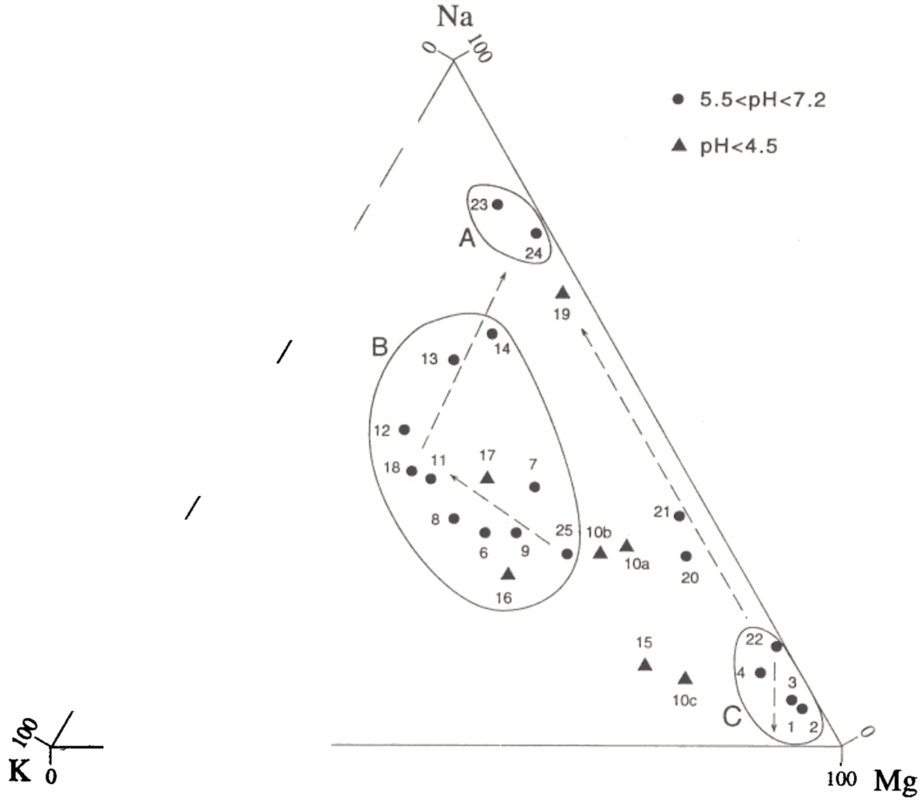

Fig. VIII.9 - Chemical data plotted on a Na-K-Mg triangular plot. To illustrate the water rock interactions Ca, which is the most abundant cation, has not been considered, whereas magnesium is assumed to be indicative of a water interaction with limestones. Group B represents waters circulating in the volcanic rocks. In this group two possible mineralization trends can be observed: a trend showing an increase in Na-chloride (at the western margin of Alban volcanic edifice) and a second trend showing an increase in alkaline bicarbonates due to the leaching of host rocks by acidic, gas-rich waters (inside the Alban complex edifice). Group C includes the waters circulating in the karstic aquifers: in the figure a line, trending toward Mg, indicates an increase of sulphate due to the leaching of the Triassic basement (deeper karstic aquifer). Group A represent waters diluting trapped ancient sea water at depth. Waters from the Acque Albule springs (20-21) lie on a line which shows a mineralization trend from the alkaline earth-bicarbonate and sulphate type towards the Na-chloride type. Finally, the acid sulphate waters, due to the gas bubbling (CO_2, H_2S) in shallow waters are scattered in the diagram.

in these springs which increases the reactivity of the water towards the vulcanic units. In this group it is possible to observe two mineralization trends (fig. VIII.9) which show: *i*) an increase of sodium and potassium (with an almost constant Na/K ratio) as well as an increase in bicarbonate in the springs located in the western volcanic belt area (25, 6, 7, 8, 9), linked to silicate hydrolyses in presence of a deep origin CO_2 excess; and *ii*) a relative increase in sodium chloride in the springs located at western margin of the volcanic system (18, 12, 13, 14). It is worth noting that during a seismic crises (May-June 1981 seismic swarm) the water of Pozzo Co.Mi.Ro. (18) showed a significant increase in temperature, from 18°C to over 40°C. At the same time a clear increase in the Na-chloride content was also observed. In this case the NaCl may indicate the existence of a deep fluid circulation component.

b) The alkaline earth bicarbonate and sulphate type waters have salinity values in the range 1.2-2.5 g/l, indicating a complex and deep circulation in the buried karstic aquifer.Samples of this type include a small group of springs located at the north-eastern margin of the volcano edifice (Colle Foce, 1; Passerano, 2; Acqua Solfa, 3; Acque Albule 1, 20; Acque Albule 2, 21). If compared with Ninfa's chemistry, considered as pure term of water related to a relatively shallow karst aquifer, it is also possible to observe two mineralization trends in this group (fig. VIII.9): the first one is linked to an increase in calcium sulphate (1, 2, 3) while the second one shows an increase in sodium chloride content (20, 21). The first group of waters may be related to deep (and cold) circulation in the Mesozoic limestones and to the leaching of Triassic sulphates. These waters, once mineralised, probably rise along faults. The waters of the second group (20, 21), which have higher temperatures (23÷24 °C), can be coupled to mixing of bicarbonate waters from a relatively shallow karst aquifer with waters circulating at depth in the buried (thermal) karst aquifer. As compared to the first type these waters (20, 21) also show an increase in sodium chloride, indicating that the deep component should also be enriched in Na-chloride. This hypothesis has been confirmed during the seismic swarm occurred in the Alban Hills in May-June 1981 when the sodium chloride content in these waters doubled.

c) The alkaline chloride waters of the Pozzo Fogliano well (23) (about 1000 m deep) and of the Laghi del Vescovo spring (24) in the Pontina Plain have quite high sodium chloride concentrations (up to 7 g/l) and temperatures of 48 and 19°C, respectively. These waters are probably derived from the mixing of shallow ground water with fossil sea water trapped in the Pontina Plain sediments. Pozzo Fogliano was drilled in a high deep structure while the Laghi del Vescovo emerges in correspondence of a regional fault system.

d) The acid sulphate waters, whose chemical characteristics vary greatly both in space and in time (seasonal variation), usually have pH values ranging from 2.2 to 4.1. These waters (Cava dei Selci, 10; Solforata I and II, 15; Grotta Dauni, 17; Tor Caldara (Lavinio), 19) are mainly from water pools in areas with gas vents. The chemical characteristics of these waters are linked to the gaseous activity. The H_2S, which range from 0.4 up to 3-4% (v/v) in the gas emanations, is oxidised near the surface to sulphuric acid. The acid waters locally alter the host rocks and bring alkaline and alkaline earth (often iron and aluminium) into solution.

Isotopic studies indicate that he gases associated with these waters are of deep origin and have a volcanic component. This has been confirmed by a study on noble gas distribution (^3He; Hooker, *et al.*, 1985). Therefore, even if these waters should be considered shallow waters, they are significant in the understanding of fluid circulation in the Alban Hills area; in fact they should be considered as representing the final stage during the rise of a deep flow along preferential pathways, such as fracture and fault systems. This deep flow is often masked by shallow aquifers.

From the chemical data, no significant evidence of water exchange between the deep karstic aquifer in the Mesozoic limestones and the shallow aquifers in the Alban volcanic complex seems to exist in the Alban Hills area. The chemistry of the analysed waters seems due mostly to subsurface processes which involve the leaching of host rocks by shallow water enriched in a gas phase of deep origin (mainly CO_2 and H_2S). Only in the marginal zones, waters enriched in sulphates (1, 2, 3 and, to some extent, 20 and 21) and in Na-chloride (23, 24) testify an upwards flow of deep water; this water, depending on the location, rises along faults after leaching the Triassic basement or after diluting fossil sea water. Nevertheless, upward gas flow can be observed almost everywhere in the Alban region in correspondence with fracture and fault systems. This observation suggests that an upwards flow of fluid (liquid and gaseous; gaseous definitely) even if masked by shallow aquifers, may exist. The increase of Na-chloride in the waters of Pozzo Co.Mi.Ro. and in Acque Albule during a seismic crisis may confirm this hypothesis. The degree of exchange between the two aquifers is small, certainly within the error limits of the water balance analysis; this fluid exchange, when it exists, is localised and corresponds with a high deep structure as well as faults. This observation can be of certain importance in structural studies as well as for geochemical seismic monitoring (Calcara *et al.*, this volume).

The use of the chemical data to calculate the temperatures of possible reservoirs in the Alban region has been considered even in the earlier papers (Duchi *et al.*, 1991; Giggenbach *et al.*, 1988). As the water mineralization in the area involves mostly subsurface water-rock interactions, often not at equilibrium, the use of more common geothermometers is rather difficult. Nevertheless, most authors indicate possible temperatures of less than 100°C for the north-eastern area (Acque Albule) and of about 150 (or less) for the western part of the Alban region, the maximum being inferred for Tor Caldara (Lavinio). On this basis only the western margin (Ardea-Lavinio-P.Fogliano) of the Alban region is considered of interest for fluids of medium enthalpy (at least). It is possible, however, that the existence of fluids with higher enthalpy may be masked by the shallower karstic circulation in the eastern region and by the shallower aquifers in the volcanic rocks and/or in the sand of the Plio-Pleistocene sequence in the western margin. This hypothesis appears to be supported by the change in temperature and chemistry of some waters during seismic crises, such as: the increase of Na-chloride in A. Albule and the increase in temperature and Na-chloride in P. Co.Mi.Ro. (1981 seismic crisis); the increase in temperature (up to 70-80 °C) of the Pozzo delle Barozze waters (Rocca di Papa, inside of the central volcanic edifice) observed in 1988 after a minor earthquake (Calcara *et al.*, this volume). In the latter case no variation on chemical parameters was observed, suggesting an interesting hypothesis: the upwards flow of steam through a local fault reactivated by the earthquake. Further studies should be carried out in the area to verify the effectiveness of the Plio-Pleistocene complex as hydraulic barrier and the nature of deep fluids, taking in account such factors as the temporal variation of water and gas chemistry, mixing phenomena, the possible link between geochemical parameters and structural setting and the seismicity of the region.

CONCLUSIONS

Local hydrogeological studies indicate the existence of two main aquifers, one located within the Alban volcanic complex and the other in the calcareous-siliceous-marly basal complex.

Groundwater in the volcanic deposits is essentially cold, and only locally does it receive gas leaks from the buried basal aquifer (Mesozoic carbonate reservoirs). Regardless, these deep origin contributions do not imprint any thermal character on the volcanic aquifer.

The top of the basal carbonate aquifer is limited by a low permeability cover (Pliocene-Pleistocene) that separates it from the overlying volcanic aquifer; this is deduced indirectly from:

a) the analysis of ejecta from several peripheral vents, distributed throughout the Alban Hills area, which generally reveal the existence of the Plio-Pleistocenic clay deposits at depth;

b) geophysical investigations;

c) boreholes for water prospecting;

d) water balance of the Alban Hills area.

The basal Mesozoic hydrostructure occurs in calcareuos-siliceous-marly terrains, referred to as the Sabina Series, and in the regional neritic karstic substratum (Lower Lias-Upper Trias).

The hydrogeological and structural setting of the pre-Apennine area allows one to hypothesise a hydraulic continuity between the Mesozoic hydrostructure (buried by Plio-Quaternary terrigenous deposits) and the large karstic aquifer (located at the eastern / south-eastern boundaries of the Alban area, near Lepini Mt., Prenestini Mt., Tiburtini Mt.). These conditions would be favourable for recharge of the buried hydrostructure in the Alban area (and for possible geothermal reservoirs) if sufficient permeability exists in the fissured deposits of the Mesozoic substratum.

During circulation the waters which infiltrated the sedimentary series, assume a bicarbonate composition that is essentially alkaline earth-sulfate (Tivoli, Latina Valley) or, if mixed with ancient marine waters (Pontina Plain), alkaline-chloride.

The chemistry of the waters circulating in the volcanic rocks, which is strictly controlled by CO_2, is generally described as alkaline earth-bicarbonate or (where the carbon dioxide gas pressure is higher) as alkaline-bicarbonate.

Silica and gas geothermometers indicate that low enthalpy fluids (≤ 80°C) are expected throughout the study area, with the exception of the north-western sector where medium enthalpy fluids (150°C) are predicted. Nevertheless, the increase of water temperatures observed episodically in corrispondence of seismic swarms suggests that high enthalpy fluids may be present in the deeper karstic reservoirs.

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