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Titolo

*Geological and Hydrogeochemical Characterization  
of Lake Garda - Lessini Mountains' Thermal Zone*

Tesi di dottorato

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2015

*Geological and Hydrogeochemical Characterization  
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*A chi ha creduto in me....*

# ABSTRACT

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The purpose and scope of this PhD thesis is to define the possibility of utilizing the geothermal resources in the North East of Italy and, precisely, in the Province of Verona. Since Roman times hot springs in the Verona province have been used in Sirmione and Caldiero. After the XIX<sup>th</sup> century other geothermal anomalies were observed and, consequently, new wells were built. A study of the groundwater circulation and of the features of the reservoir can lead to a sustainable exploitation of this resource. A tectonic-structural review of the area, shows that there is a link with the geological structures in the Southern Garda lake area and Verona Province. Generally the Po Plain's younger terrains form the cover of thick reservoirs of fluids, located in the underlying carbonate formations. Subsequently, the processing of temperature data collected in duly selected wells, shows, on the one hand, evidence of thermal anomalies and, on the other hand, the assessment of the geothermal gradient. When values higher than normal are detected, the geochemical-isotopic characterization of water samples allows us to find out the origin and the age of the groundwater, and to constrain the mixing processes affecting groundwater circulation. The data of this research can be used as input parameters in geothermal modeling, allowing to draw a geothermal map of the research area.

## RIASSUNTO (in Italian)

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Scopo di questa tesi è di definire la possibilità di utilizzo della risorsa termale della Provincia di Verona. Durante il dominio dell'Impero Romano si conoscevano già le sorgenti di Caldiero (Vr) e di Sirmione (Bs). Dopo il XIX secolo furono terebrati i primi pozzi di acqua calda in seguito allo studio di aree dove si sono riscontrate anomalie geotermiche. Una ricerca attenta della struttura tettonica dell'area analizzata collega la risalita di acqua calda a faglie beanti e permette la localizzazione di bacini di raccolta di tali acque nelle formazioni carbonatiche. Misure della temperatura di acqua calda prelevata da alcuni pozzi ci hanno permesso di calcolare il gradiente geotermico dell'area. Ulteriori ricerche mediante l'utilizzo di analisi chimiche ed isotopiche effettuate su numerosi campioni d'acqua dell'area studiata, pozzi e sorgenti di acqua fredda e calda, hanno permesso di acquisire più informazioni mediante le quali si possono ipotizzare sia le probabili circolazioni della falda sotterranea sia le caratteristiche del bacino di raccolta. Quindi considerazioni geologico-strutturali e idrogeologiche-geochimiche suggeriscono la presenza di un serbatoio carbonatico profondo sede di circolazione dei fluidi termali che sono visibili nell'area orientale, lungo la fascia pedecollinare nella zona di Caldiero, mentre captate da pozzi verso occidente. Non si può certo trascurare l'ipotesi di risalite dirette di fluidi termali in superficie lungo le discontinuità tettoniche della fascia ai piedi dei Lessini che non sono visibili a causa di un loro mescolamento con acque fredde superficiali. I risultati raggiunti in questa tesi mettono in evidenza interessanti sviluppi scientifico applicativi nell'area benacense tra Sirmione e Lazise/Peschiera, nell'area tra Sant'Ambrogio di Valpolicella e Pescantina e nella fascia pedemontana. Ulteriori sviluppi potrebbero essere, oltre a quelli già presenti di balneoterapia, l'utilizzo per l'itticoltura o per il riscaldamento mediante scambio di calore per edifici pubblici e privati.

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# PRESENTATION OF THE THESIS

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The subject of this PhD thesis concerns the study of the thermic areas of the Verona Province.

Indeed, the considered sector of the Southern Alps and of the adjacent Po plain, remain relatively poorly studied, in spite of their position within the Alpine orogeny and their tectonic history. Here, new data are provided in order to improve knowledge about the processes that characterize the deformation of this area.

The disciplines presented in this work are basically geophysics and geology, and, particularly, geochemistry, hydrology, structural geology, geothermic. Specific methodologies were applied to different data sets such as a wide geophysical research with HVSR method, and seismic reflection in the Caldiero area; chemical and isotopic analysis in the whole area. Two different approaches were used: the first was based on the study of the effects of past deformations, which were observed directly in the field with tomographic instruments or with waves induced; the second, with the complete study of the water of the area taken into consideration analyzed.

Original contributions already published or submitted for publication are provided given in appendix.

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# CHAPTER 1

## *Introduction*

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In ancient time the thermal waters were used as medicines and to cure people from the ills. In Italy many mineral waters were used from the Romans where built efficient spas for relax and joy. The thermal localities of Sirmione and Caldiero were known since Roman age but, perhaps, from pre-roman people.

In first academic year the bibliographic analysis has played an important role to decide on starting and what to base research on to identify thermal anomalies of the territory studied.

The ancient and present examination of several geological and chemical conditions provided new data for the interpretation of hydrothermalism in Western Veneto.

My purpose is to evaluate exploitation of Verona province as a possible source of thermal anomalies and sustainable uses of hot water resources.

This research will permit us to draw up cartographic-based boundaries of the Veronese thermal areas, divided in four thermal districts with Sirmione area where thermal fields were detected because they seem to show the similar homogenous, geological, thermometric and chemicals conditions.

The eastern plain thermal district is mainly around the little town of Caldiero, but it also includes the municipalities of Belfiore, Colognola ai Colli, Lavagno, S. Martino B. A., S. Bonifacio, Zevio, Ronco all'Adige and Arcole. In this area, the temperature of the fluids fluctuates between 15 °C and 31 °C. Those peculiar hydrogeological characteristics allow conditions of flowing artesian phenomena and the emergence of the ancient springs of Brentella and Cavalla in Giunone spa, the only thermal groundwater emergences of the province of Verona. The other thermal district, that we can generally call northern plain thermal district, is divided into two different areas. The same hydrogeological conditions define the eastern part of this district, which includes the thermal field of the municipalities

of the towns of Sant'Ambrogio di Valpolicella, San Pietro in Cariano and Pescantina. The western part includes the morainic area thermal fields of the towns of Pastrengo, Lazise, Bardolino, Peschiera and Castelnuovo. This district spreads between the towns of Sirmione (BS) and Sant'Ambrogio di V.lla where the highest subsoil water temperature decreases from West (about 70 °C) to East (46 °C). Reports of wells showing thermic anomaly at low thermalism (15 °C - 22 °C) are rare outside the thermal districts which are considered more reliable for warm water discoveries. This situation proves the vast extent of the hydrothermal system and the existence of complex hydrogeological phenomena which causes the fluid movement.

In the hilly, alluvial and morainic zones of the province of Verona the subsoil lithological and hydrogeological situation has been studied using seismic geophysical methods. Between first and second year, more of 100 recordings were made using a tomograph recently produced, called the Tromino (Albarelo, 2007; Castellaro et al., 2005). This tool allowed me to investigate the area around the spa Caldiero, determining, with the help of the stratigraphy of some wells, the substrate (e.g. Appendices H). To further definition of the substrate, the use of geoelectric surveys NS and EW direction was planned. This research could highlight volcanic chimneys such as, Mount Gazzo and Mt Rocca, near Caldiero spa, may be preferential ways for the ascent of hot water (Canatelli C., 2011; Galgaro et al., 2013). At the same time for the examination of statistics I have tried to relate the rainfall in the hilly north of Caldiero with the reach of more than 10 years of Brentella well, well spa town, but I did not find any significant correspondence. The programs used were Minitab, and after the suggestion of Professor Salmaso, Statigraphics.

Between the months of July and August of the first year, after analyzing approximately 1000 wells in the studied area, I considered 46 important sites for sampling water both hot and cold. These samples are used to define the origin of such water, and then the traffic routes. To create a model of movement it's necessary to make isotopic analysis. The samples taken are only 16 because some owners of spas do not agree to give permission to take samples.

In the last months I finished to analyse the samples of water from wells and springs studying the isotopes of some elements of these waters. Sr isotopes are analyzes in the laboratories of

Geosciences dell' Igg of Padua with the help of Dr. Giancarlo Cavazzini while  $^{18}\text{O}$ ,  $^3\text{H}$  and D in the laboratories of IGG-CNR. of Pisa, and S in Canada laboratory.

From the analysis I saw that the salt content in thermal water depends on different factors and it tends to increase as long as the fluids flow underground, whilst its chemical composition is influenced by the rock types with which the water comes in contact. As long as the temperature increases the thermal waters get less sweet but slightly brackish. Sulfates are a result of the exchanges with the deep rock reservoir characterized from mineral evaporitic origin (dolomite and limestone dolomited). The chlorides may be related to the presence of marine origin sedimentary rocks which are not fully consolidated and still containing brackish water. They form the upper part of the pre-Pliocene Po substrate. The hot and cold waters in the Veronese area are quite homogeneous in their chemical composition, and they belong to the single sulfate- bicarbonate-alkaline earth family in which the most significant chemical changes in thermalized water concern mainly about their total salt content, their composition, and in particular the anionic bicarbonate / sulfate + chloride ratio. The hydrochemical survey allowed to classify the thermal waters of the Caldiero using the Piper diagram. In the Eastern Plain Thermal District warm waters are calcium-bicarbonate, almost sulphate with a modest amount of alkalis (Na + K) but with significant quantity of magnesium. Thanks to their chemical nature these waters belong to the bicarbonate-calcium-magnesium primary alkaline earth facies, secondary sulphate-calcic facies. In the thermal areas of the province of Verona from the analysis carried out, it also notes that the TDS is greater than about twice the east than in the west of Caldiero. This is due to the temperature of 26 °C degrees Caldiero compared to the 40-50 °C area of Piovezzano-Lazise to the west. That means that the circulation and crossing in the rocks are different. By means of the few analysis performed and based on the historical ones I can assume two different types, or more, of thermal groundwater. The first type, a carbonate reservoir, is contained in the pre-Quaternary rock substrate rocks of the plain and the deep sub-alpine and alpine layers, where there is intense hydrothermal fluid movement with little or no connections with the cold surface water systems. A clastic type reservoir is made of Quaternary sediments melted in the plain whose hot fluid concentration is related to the dispersals and to the landfill of the deeper rock hydrothermal system.

## CHAPTER 2

### *Geographic Location*

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#### *2.1 Geographical location*

The study extends along the southern boundary of the Alps, mostly within the Verona and Brescia provinces (north-east Italy).

In order to define the characteristics of the warm and hot waters between the area of Sirmione and Caldiero, their origin and path in the subsoil, the research was extended in an area of about 5000 km<sup>2</sup> including the Trento Province. In detail the study area comprised the Geological sheets n°49 “Verona” (Bosellini et al., 1967) and n°48 “Peschiera” (Carraro et al., 1969) n°35 “Riva del Garda” (Cadrobbi et al., 1948), n°36 Schio (Castellarin et al., 1968) at the scale 1:100.000 (ISPRA), and the Geological sheets, n°080 “Riva del Garda (Castellarin et al., 2005a), n° 059 “Tione” (Castellarin et al., 2005b), n°042 “Malè” (Dal Piaz et al., 2007) and n° 060 Trento (Avanzini et al., 2010) at the scale 1:50.000 (CARG Project).

The geomorphological characteristics are heterogeneous in the studied area. Verona province is mountainous at North with gentle decrease in elevation towards the South till the piedmont plain; Trento Province consists of mountains cut by deep valleys, as well as the Brescia Province, where mountains slope make the Lake Garda shore (Fig. 2.1).

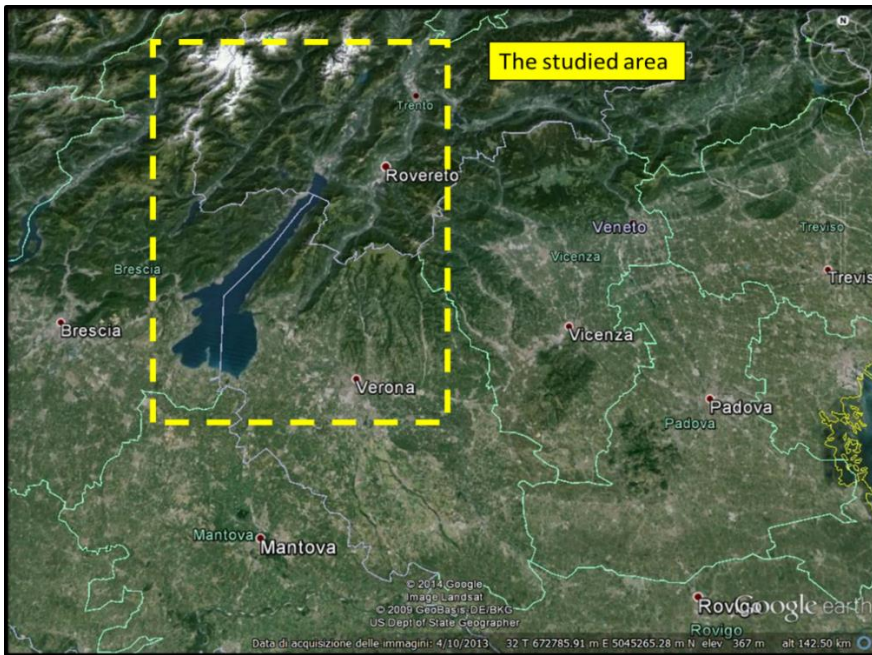


Fig.2.1 - Image of studied area by Google 2013

## 2.2 Meteorological data of the studied area

In the studied area, about 6000 km<sup>2</sup>, meteorological historical data show many differences for the various landscapes, such as mountains, hill, lacustrine and plain. I divided the area in three portions, where the official weather stations are located: a) Lake Garda; b) Verona Province; c) Trento Province.

a) The Lake Garda basin covers an area of 2290 km<sup>2</sup> (Fig. 2.2). The present situation at Lake Garda shows the highest precipitation amounts in autumn with nearly 400 mm. For winter and spring we find approximately 370 mm going down to below 250 mm in summer. A remarkable impact of climate change on the hydrological balance of Lake Garda is glaciers and permafrost (the permanently frozen subsoil) melts. River Sarca, the main tributary of Lake Garda has its spring at the Mandrone glacier. Even many tributaries of the river are originated from glaciers. In Trentino the last two decades (since 1981) was characterized by a very marked deglaciation, that it is accentuated further in these last 4-5 years. During these years the rate of reduction glaciers is greater than twice the average of the last twenty years (Piccolroaz et al., 2013).

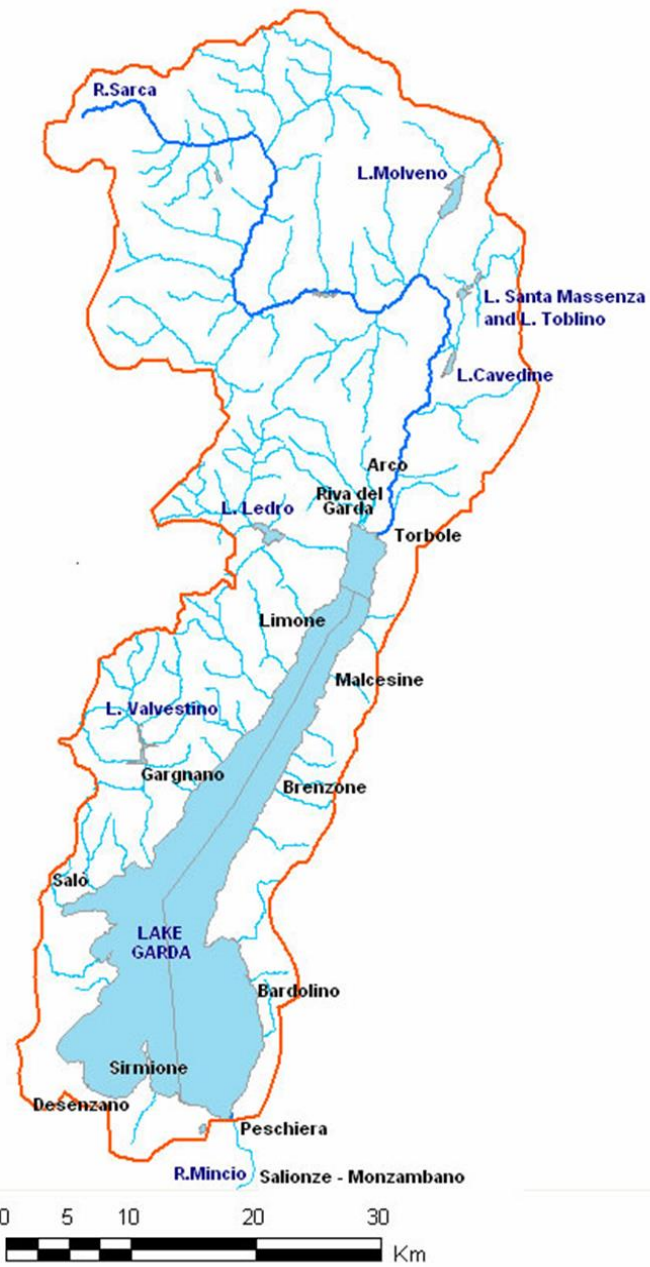


Fig. 2.2 Lake Garda basin hydrology with principal towns (Piccolroaz et al., 2013)

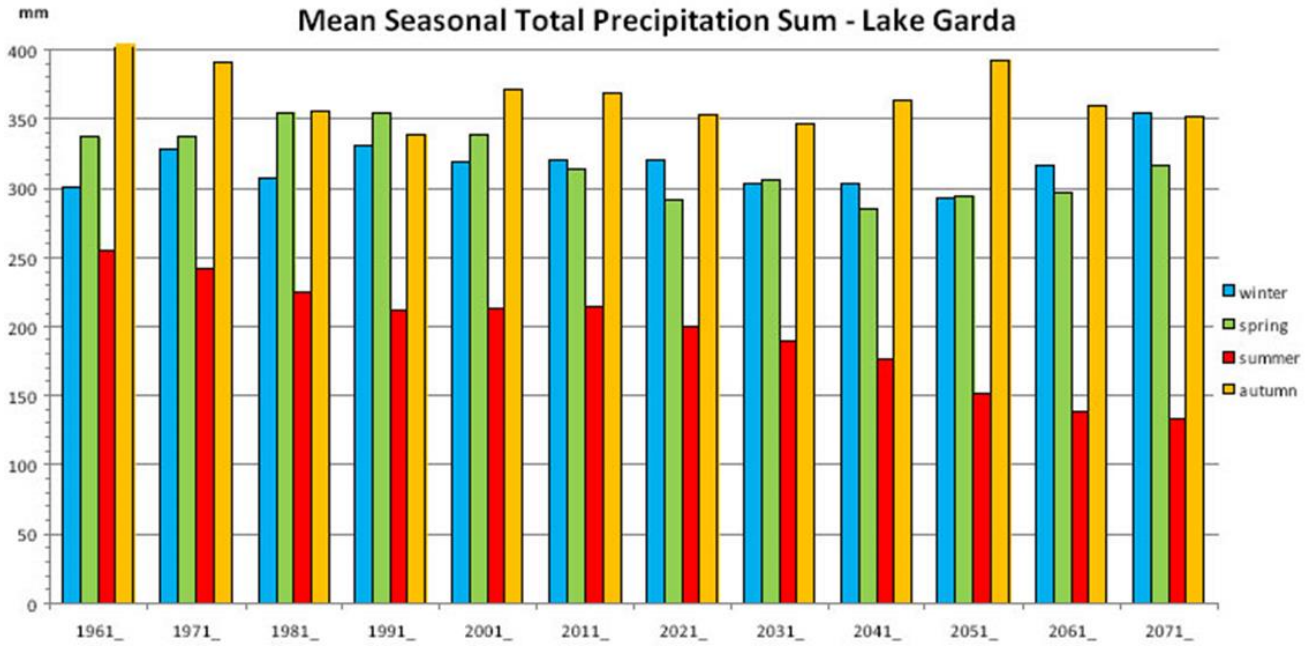


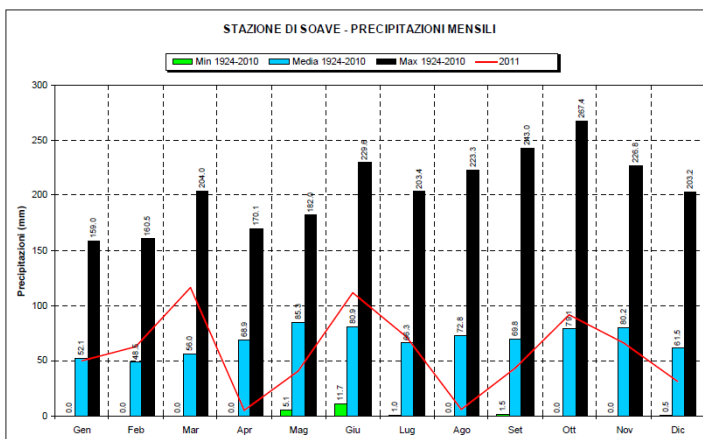
Fig.2.3 - Means of seasonal precipitation sums in the Lake Garda region between 1961 and 2100 (Züger, Knoflacher 2011)

The middle temperature of the Lake Garda shadow water is 12°C but decreases to 8°C at 100 meters of deep. The middle temperature among 1961-1990 shows middle January temperature +3°C and middle July temperature +23, 4°C.

b) For Verona, Villafranca station, the meteorological data are:

Verona Villafranca (1981-2010)	Stagioni			
	Winter	Spring	Summer	Autumn
T middle max °C	7,4	18,4	28,9	18,4
T middle min °C	-0,6	7,8	17,8	9,1
Rainfall (mm)	188,3	232,1	233,3	783,3

The middle temperature of the coldest month, January, is 2, 5 °C while the temperature of hottest month, July, is 24, 4 °C.



c) In Trento station meteo is 243 meters s.l.m. The middle temperature of the coldest month, January, is 1,6 °C while the temperature of hottest month, July, is 22,4 °C.

<b>Trento</b>	<b>Stagioni</b>			
<b>(1981-2010)</b>	Winter	Spring	Summer	Autumn
<b>T middle max °C</b>	6,3	17,1	26,9	16,5
<b>T middle min °C</b>	0,9	7,1	15,7	8
<b>Rainfall (mm)</b>	162	248	266	269

# Chapter 3

## *Geological Framework*

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### *3.1 Introduction: The geological history of the Southern Alps*

The studied area has a complex geological framework related to the multi-phased Alpine tectonics over an inherited Mesozoic paleotopography (Rogledi, 2013, Scardia et al., 2015). The Southern Alps are a preserved portion of the Jurassic continental margin of the African Plate (Masetti et al., 2013; Fantoni e Franciosi, 2010). The sedimentary extensional tectonics during the Norian-Liassic time span caused the rifting of the continental margin and the emplacement of the oceanic crust. This rifting phase has been recognized in the whole Southern Alpine area (Winterer and Bosellini, 1981; Bertotti et al., 1993).

At the end of the Early Cretaceous, the inversion of tectonic plates kinematics caused the inversion of the motion with the onset of the convergence between Europe and the Adriatic promontory of the African Plate, which controlled the subsequent pre-collisional, collisional and post-collisional evolution of the Alps up to their present setting (e.g., Dal Piaz, 1995).

The Alpine belt originated from the Late Cretaceous to the Present convergence with the European plate subduction under the Adriatic microplate (Dewey et al., 1989; Kurz et al., 1998; Dal Piaz et al., 2003). The Alps are made up of a Europe-vergent collisional wedge (Alpine domain) and a south propagating fold and thrust belt (South Alpine domain) separated by a major fault system, the Periadriatic Lineament (Fig. 1).

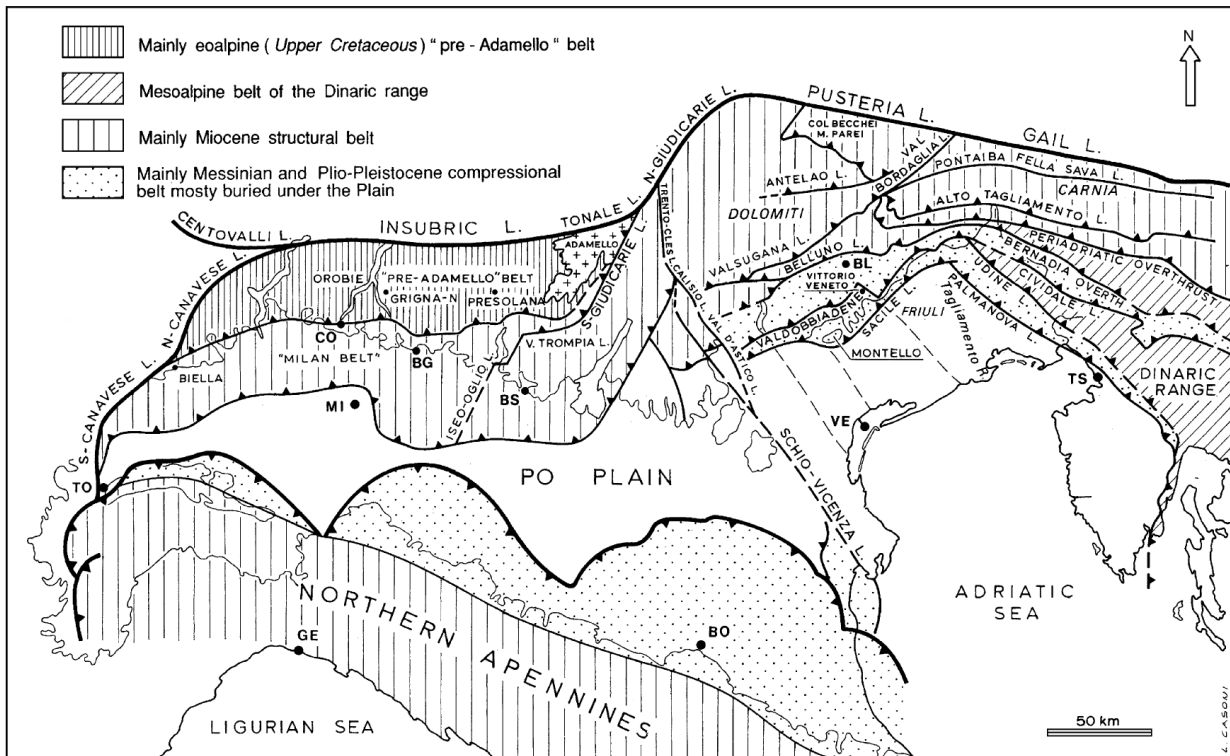


Fig.3.1 – Simplified structure of the Southern Alps. Geometrical relationship with the southern foreland zones, Po Plain and Northern Apennines, from Castellarin et al., 1992.

During the first stages of the Alpine orogeny (Late Cretaceous–Early Palaeocene), the central and western Southern Alps constituted the slightly deformed hinterland of the Europe-vergent Austroalpine-Penninic collisional wedge, while the eastern Southern Alps were involved in the Dinaric phase till the middle Eocene. Post-collisional erosion affected the Lombardian sector in the Oligocene (Sciunnach et al., 2010). From the Miocene onward, the Southern Alps were shortened as a south-vergent fold and thrust belt, which developed as a retro-wedge (Castellarin et al., 2006; Doglioni and Bosellini, 1987).

During the Pliocene-Quaternary time the Southern Alps were affected by the ongoing deformation of the Northern Apennines (Ghielmi et al., 2012; Scardia et al., 2012) and the southalpine foreland became the Apennine foreland. In this switch also the triangular swell of the Adige embayment comprising the Lessini and Berici Mountains and the Euganei Hills became a part of foreland of the Apennines (Fantoni and Franciosi, 2009, Fig. 3.2) and thus the autochthonous core of the Adriatic plate.

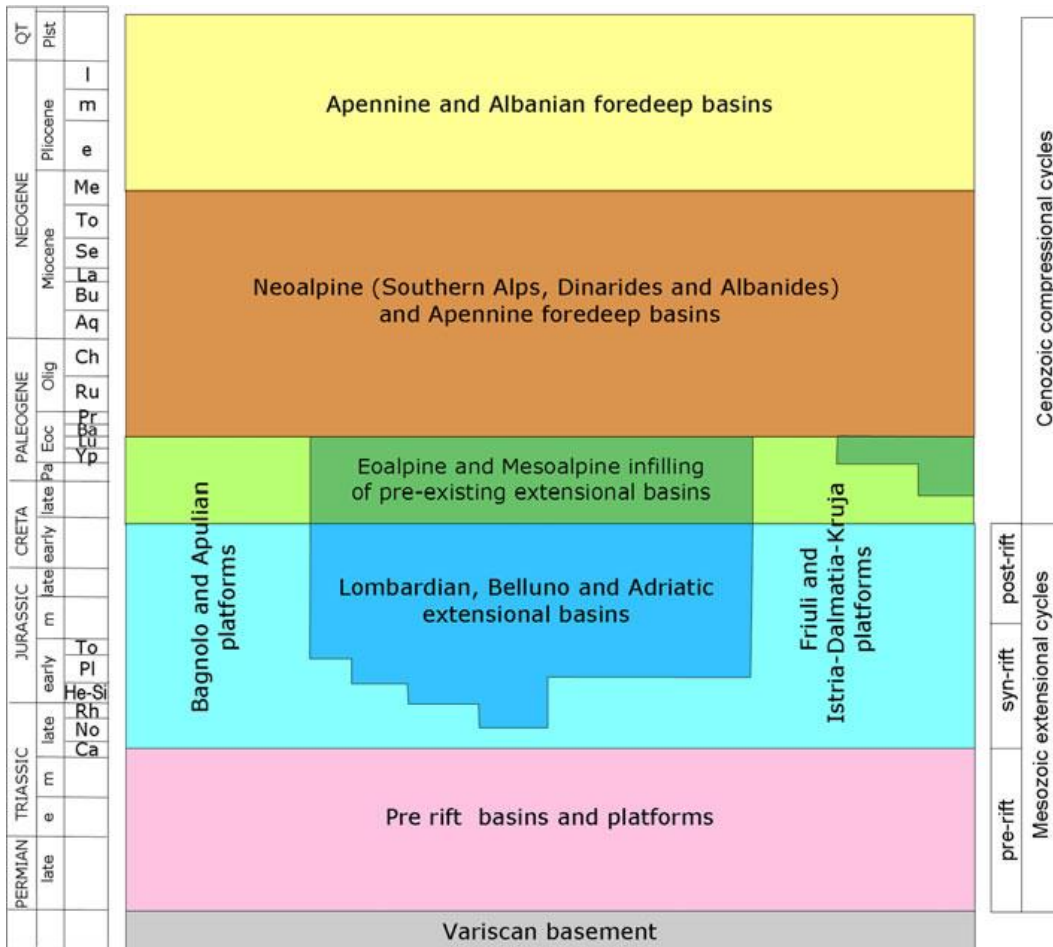


Fig. 3.2 Meso-Cenozoic tectono-sedimentary cycles (after Fantoni and Franciosi, 2008)

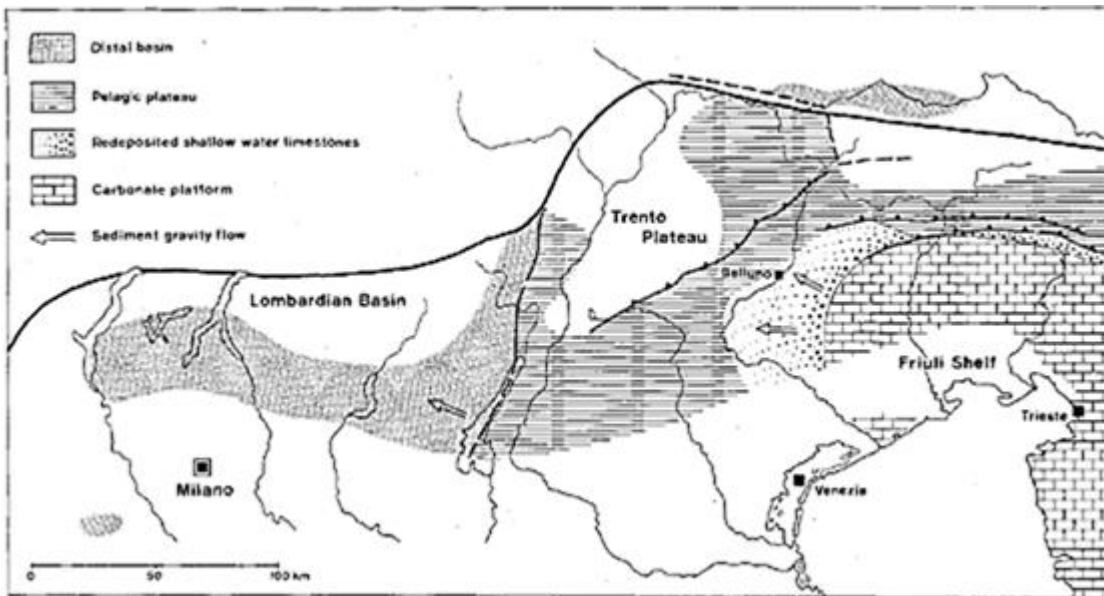


Fig.3.3 Paleogeographic reconstruction of the Southern Alps in the Jurassic (from Winterer & Bosellini, 1981)



### 3.2 Stratigraphic setting of the studied area

Despite the Alpine shortening, the Southern Alps preserved the different paleogeographic units of the Mesozoic Adriatic passive margin. From east to west they are the Julian Basin, the Friuli Platform, the Belluno Basin, the Trento Platform and the Lombardian basin. The Trento Platform was drowned during the Middle Jurassic and became a seamount (Trento Plateau).

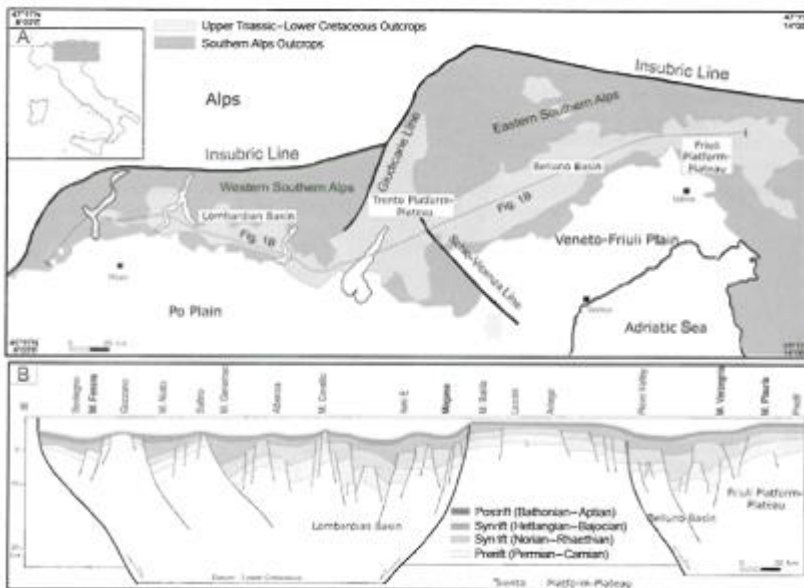


Fig. 3.2.1 – The Mesozoic structural domain in the Southern Alps outcrop (panel A). The dotted line points out the section in panel B. Section across the Southern Alps showing the extensional Mesozoic architecture of the Southern Alps at the end of the Early Cretaceous (Carminati et al., 2010).

In this area the sedimentary sequence of the Mesozoic, Paleogene, Lower and Middle Miocene was folded in a lot of structures with polarity directed mainly to the South (Pieri and Groppi, 1981). In the last years, research shows that the structural assessment is different in Po Plain (Livio, 2012). In particular in Mesozoic resulted the creation of a north-south half graben, bounded by W-E dipping normal master faults (Fig. 3.2.1; Masetti, 2012). From west to east, three important paleogeographical-structural conditioned the geology of the area: 1) a carbonate platform in the Early Jurassic that evolved into a pelagic plateau during the Late Jurassic (Trento platform and plateau) and bordered to the west by the Lombardian Basin; 2) a basin that developed in the very Early Jurassic (Belluno Basin); 3) a carbonate platform existed from the Jurassic until the Cretaceous (Friuli platform). The thickness of sedimentary covers mostly decreases from West to East above all in the correspondence of the Ballino-Garda fault, they are represented by the Mesozoic carbonate

successions and by the Lombard flysch in the western side of Giudicarie area. In the Eastern side the Lessini carbonate platform of Tertiary age developed above the Mesozoic successions. The Trento platform covers a wide area in north-eastern Italy extending north-south from the Po Plain to Bolzano. To the west it is separated from the Lombardian Basin by the Garda escarpment fault system active during the Jurassic and the Cretaceous. The demise of the Trento platform and plateau during the Jurassic was characterized by two phases during the Early Jurassic: the first phase of shallow-water sedimentation with a thick pile of the Calcari Grigi Group and a second phase of pelagic condensed sedimentation with the Rosso Ammonitico Veronese (up per Bojaccian to Tithonian). The Calcari Grigi Group is several hundred meters thick, reaching 1000 m.

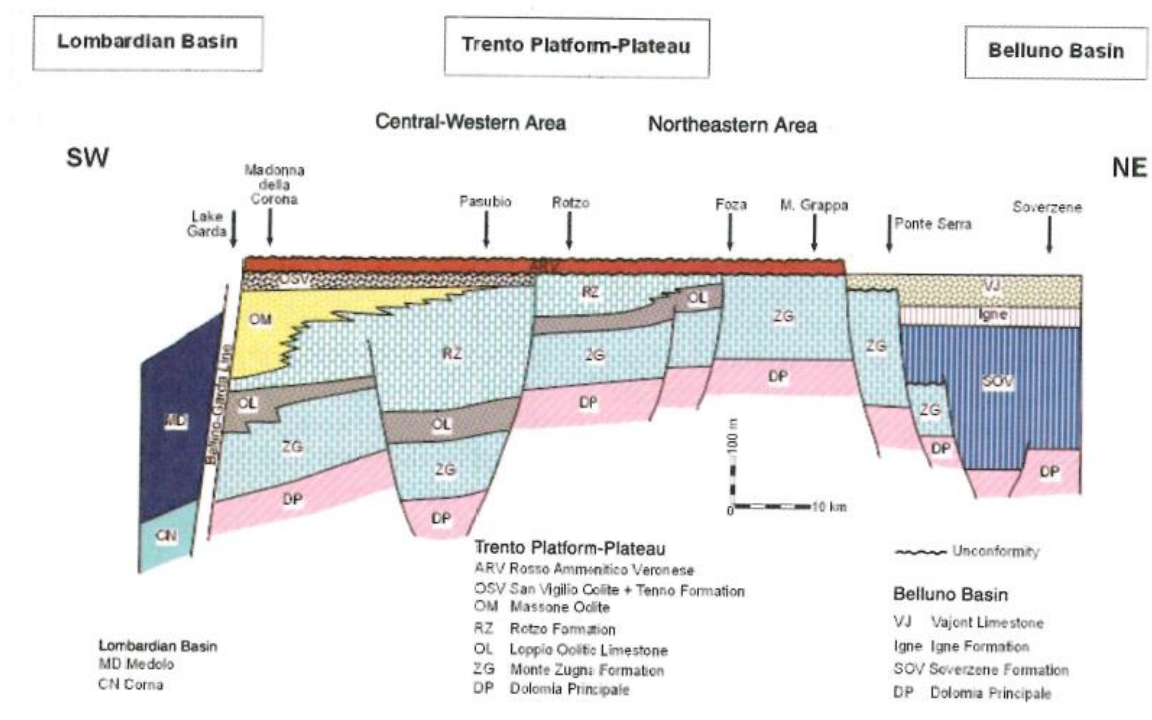


Fig. 3.2.2- Carminati et al., 2010)

The zone of separation between these paleo-morphostructural elements is Ballino-Garda fault that shows the platform–basin transition. Some authors (e.g. Doglioni and Bosellini, 1989) suggest that between Lombard Basin and Trento platform existed a middle zone characterized by pelagic sedimentation throughout the Cretaceous age (Luciani, 1989; see Fig.3.4.3). In Lombardian basin the carbonatic sequence are: Corna (or Tofino Fm. in Ballino basin with megabreccias) and Medolo. Afterwards the lombardian sequence DP, Lombardian Lake Garda, is given by Maiolica, Scaglia

Variegata and Scaglia Rossa; ending the sequence in Cretaceous age with a hardground. In the Oligocene the post-collisional sedimentation of the Gonfolite took place (Sciunnach et al., 2010).

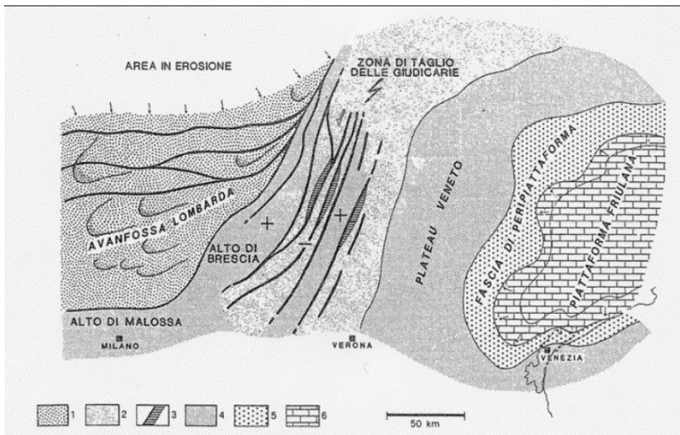


Fig.3.2.3 – Paleogeographic scheme of studied area (upper Cretaceous). 1. Flysch; 2. Variegated scaglia; 3. Black shale; 4. Red scaglia; 5. Deposits of periplatform; 6. Platform limestone (Luciani, 1989).

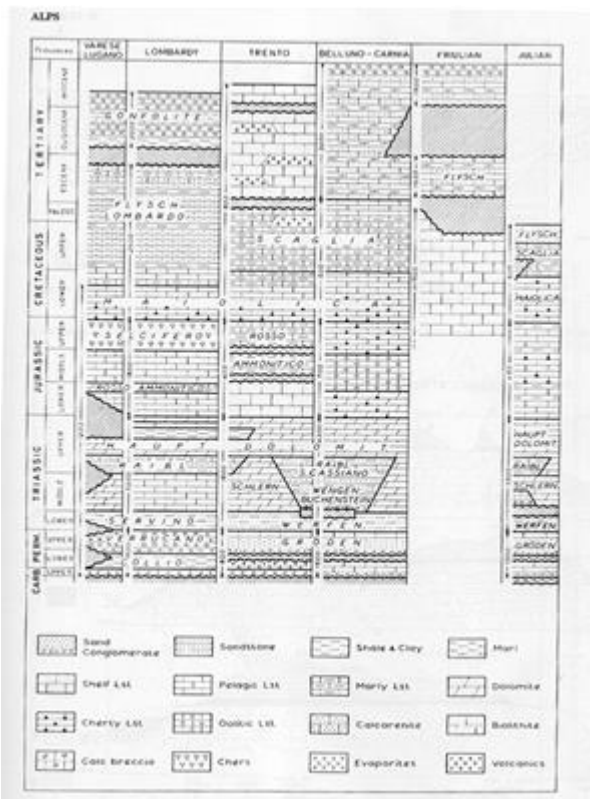


Fig. 3.2.4 – Diagram of the stratigraphy of the Southern Calcareous Alps (Pieri 1969). Thicknesses approximate in meters.

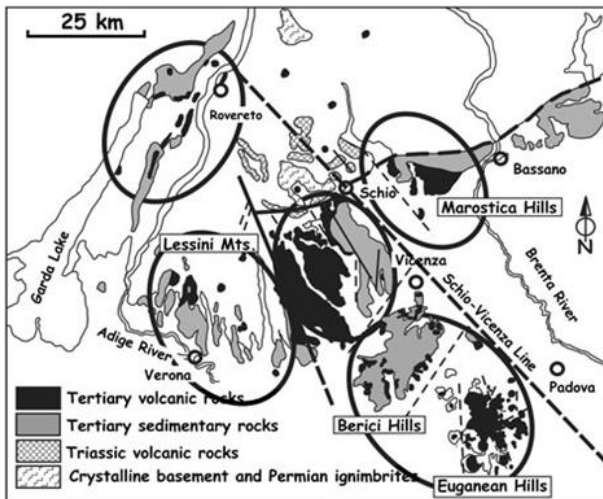
In Trento plateau, during Aalenian, sedimentation has been mainly condensed pelagic since the drowning of the carbonate platform. The Mesozoic succession ends with Maiolica and Scaglia Rossa sedimentation. The thickness of Maiolica is about 80-150 m, while 50-60 m of Scaglia Rossa.

The Veronese sequence of Tertiary is thin: Spilecco limestone, 10-15 m, Nummulites limestone, 120 m, interposed to basalts, Priabona marl. In a period of time between Paleocene and Oligocene/ Miocene

there were important volcanic events in throughout studied area.

The Paleogene magmatism in the Southalpine Unit consists of volcanic and sub-volcanic bodies covering a surface of about 2,000 km<sup>2</sup> and is named the Veneto Volcanic province. These interested two distinct areas: 1) the Lessini massif and the Marostica piedmont hills and 2) the Euganei and Berici hills. Both are characterized by distinct magmatic activities that are, in part, of different age.

Fig. 3.2.5 - Geological sketch map and location of the Veneto Volcanic province in the Southalpine (modified from Beccaluva et al. 2007). The circles show the volcanic districts.



The first area, where the present study is located, is represented by the volcanic districts of the Adige valley (near Arco and Rovereto) of middle Paleocene to middle Eocene age; by the Lessini Mts., to the West of the Castelveto tectonic lineament, of Paleocene to middle Eocene age (Visona` et al., 2006); by the area between the

Castelveto and Schio-Vicenza lineaments, of middle Paleocene to upper Oligocene age; and by the Marosticano area of middle-upper Oligocene to Miocene age. The magmatic products of these areas are mostly basic to ultrabasic volcanic rocks, which belong to an alkaline and to moderately sub-alkaline series (transitional basalts, basaltic andesites). In the area of Lake Garda the stratigraphic sequence is different in left side.

### 3.3 Geological and tectonic setting of the studied area

#### 3.3.1 The Lombardian Basin and Trento Platform

The study zone lies within the area between the domain structures of the Giudicarie and of the Schio-Vicenza fault system, which represent the major tectonic discontinuities into the Southern Alps. These tectonic structures, show the heritage of the Mesozoic paleo-structures (Scardia et al., 2015) caused by the difference between Lombard Basin (West) and Trento Platform (East).

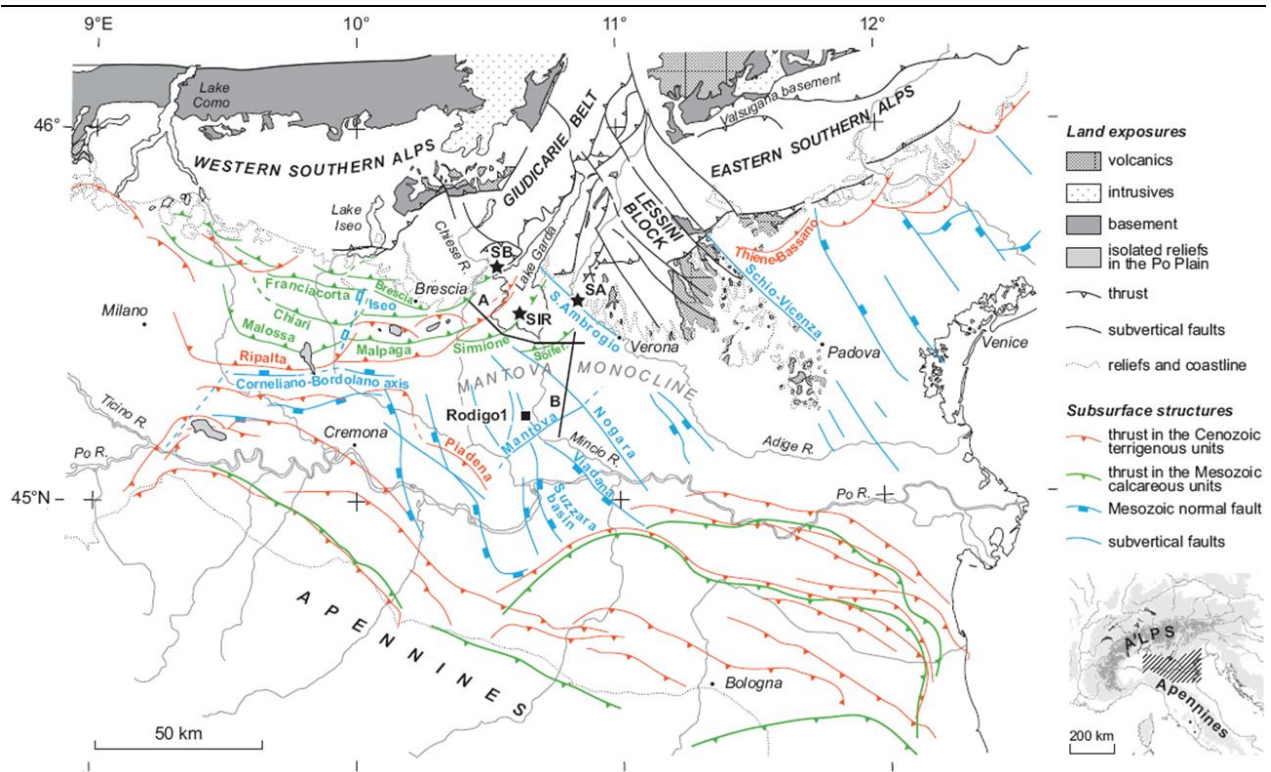
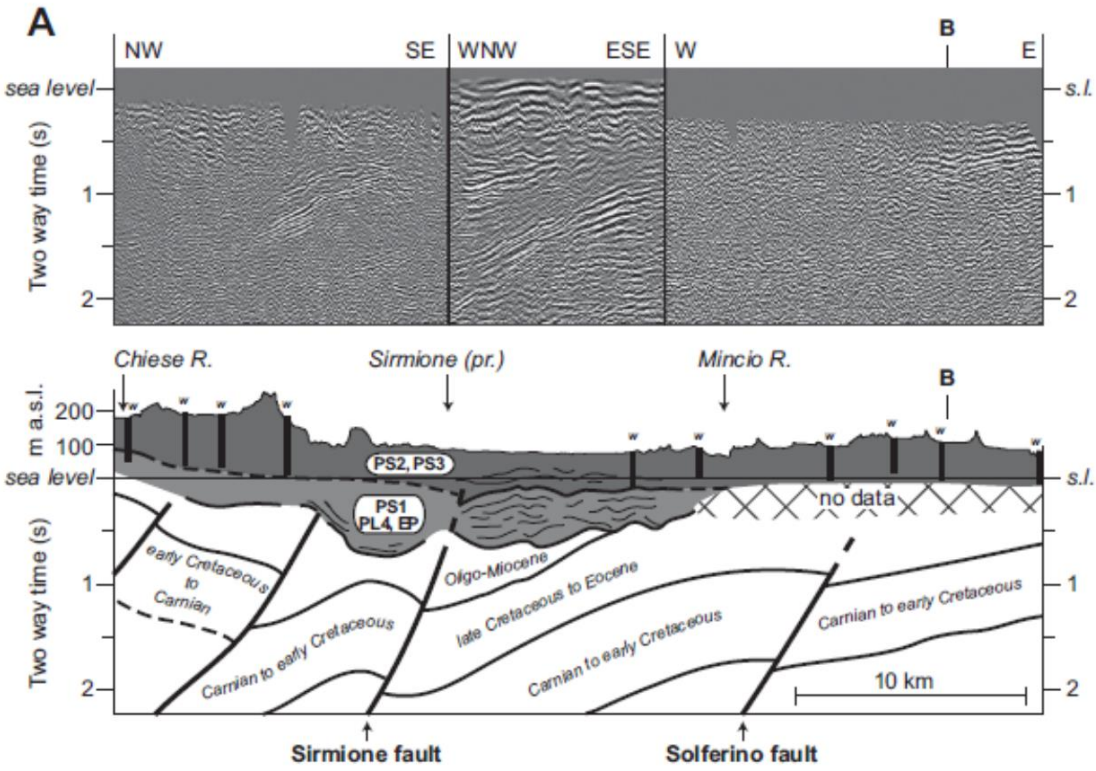


Figure 3.3.1- Structural map of the central – eastern Po Plain with the track of seismic lines A and B, and the Rodigo 1 well (black square) shown in Figure 2.3.2. Stars indicate the land exposures where stratigraphic and structural observations were carried out (SB-San Bartolomeo Hill; SIR-Sirmione peninsula; SA-Sant’Ambrogio di Valpolicella) (Scardia et Al, 2015).



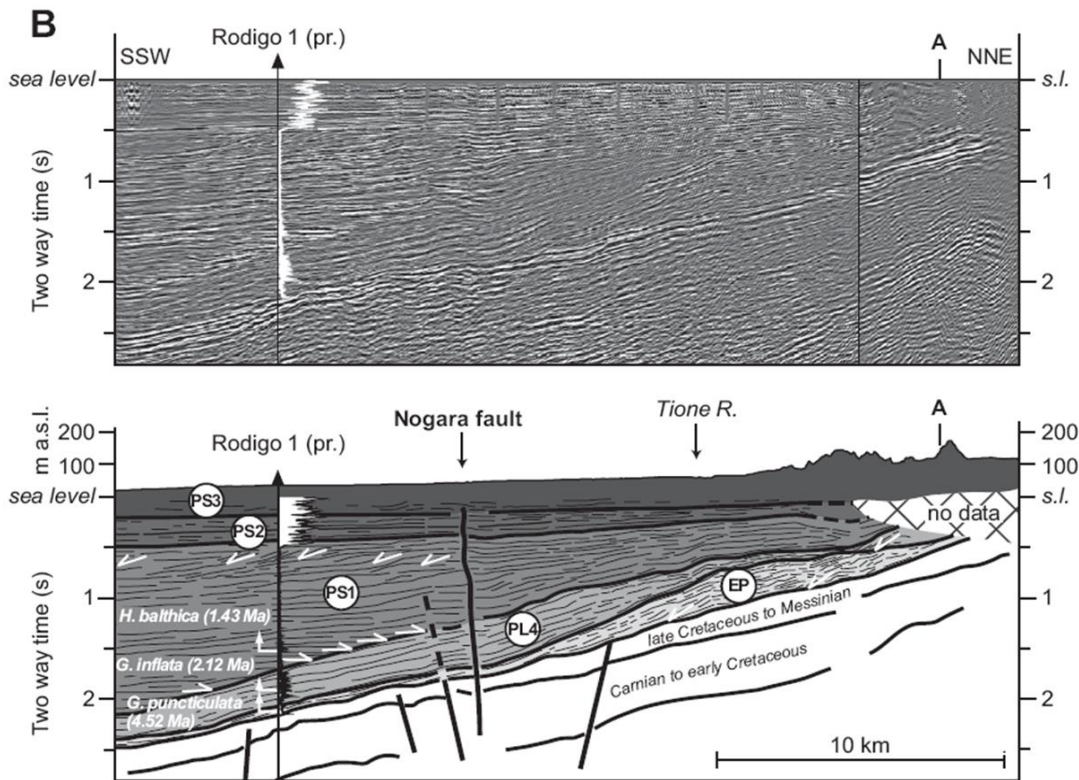


Fig.3.3.2- Representative seismic profiles from the Po Plain and related stratigraphic interpretation (line B in map). The Rodrigo 1 and water wells (w) used to calibrate the uppermost seismic horizons are also displayed. Ages of biostratigraphic events *Globorotalia punctulata*, *Globorotalia inflata*, and *Hyalinea balthica* are from Lourens et al. (2005), Scardia et al., 2015..

At the end of Cretaceous a basic change occurred in the kinematics of the plates which inverted their movement (Dal Piaz, 1993; Castellarin and Cantelli, 2001) promoting the beginning of the margin convergence that gave rise to the evolution of the Alpine orogen.

During the Dinaric phase, lasted in the middle Eocene, the eastern Southern Alps were affected by inflection toward the Dinaric chain, which was accompanied by volcanic extrusions in the Euganei–Lessini sector (Fantoni and Franciosi, 2010; Castellarin et al., 2006; Sarti et al., 1993). The Adamello magmatic cycle (Late Eocene–Early Miocene) is older as eastern volcanism. The Adamello massif is a large plutonic body of Tertiary age, which extends over an area of more than 550 km<sup>2</sup> in the Southern Alps (Callegari and Dal Piaz, 1979; Cortecchi et al., 1979). The massif is wedged between two major tectonic lineaments: the Insubric line to the north and the Giudicarie line to the south-east. It intruded through the Alpine crystalline basement and, in the southern part, also through the Permo-Mesozoic unmetamorphosed cover sequence. The body has sharp contacts with the surrounding country rocks upon which it superimposed a distinct contact aureole. The mineral ages progressively

increase from 29 m.y. in the northeastern part to 52 m.y. in the southern part of the massif. The pre-Adamello structural belt is characterized by S vergent ENE±WSW trending thrusts with large crystalline basement implications; the superposition of the big fold ramps produced severe deformations and shortening in the Orobic, Presolana and Grigna zones (Laubscher,1985). This structural system extends to the E in Val Camonica up to the western sector of the Adamello pluton which clearly postdate the tectonic deformation of the system (Brack, 1986). This belt has to be considered neo-alpine in age (Late Cretaceous) (Doglioni and Bosellini, 1988; Bersezio and Fornaciari, 1988) and has not been recognized E of the S-Giudicarie Line.

Only the Lombardian part of the Southalpine margin and foreland was constantly deformed during the Oligo-Miocene phases by consistent new shear and inversion structures (Fantoni et al. 2004); a wide triangle zone also arranged the shortening of their thick foredeep wedge.

The Neopalpine compression started in the Serravallian (Castellarin et al., 1992...) and came to an end after deposition of the Lower Messinian units and reasonably before the Pliocene (Fantoni et al. 2004; Picotti et al., 1995).

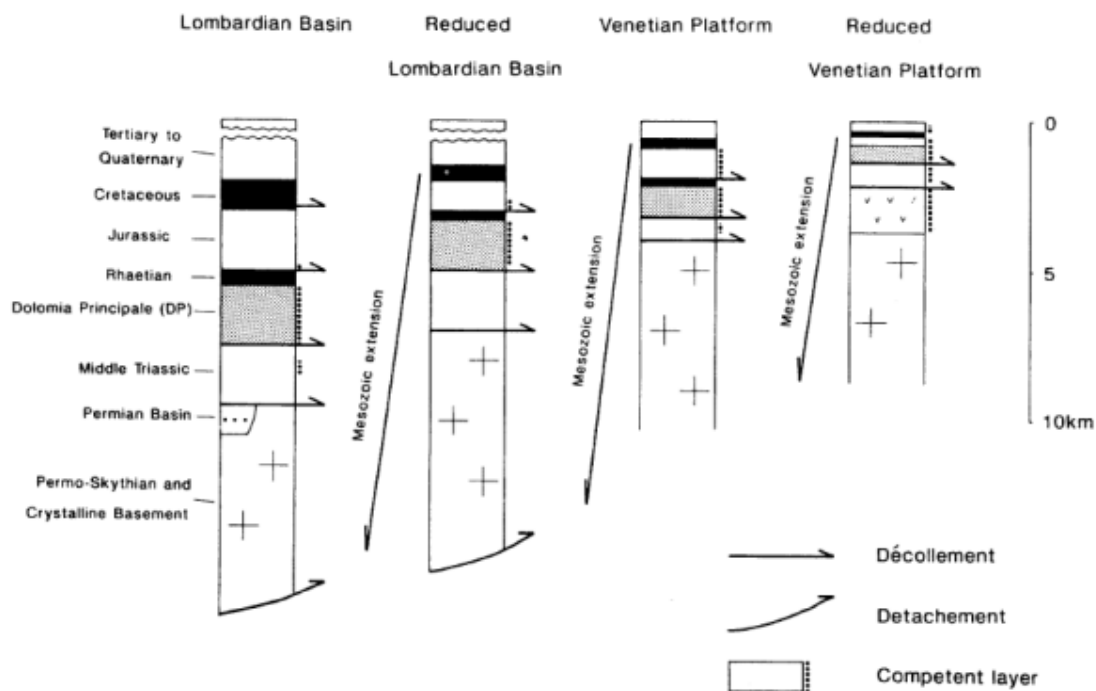


Fig.3.3.3 - Stratigraphic columns of different domains within the Lombardian basin and the Venetian platform. Thickness variations and decollement levels are shown. Basement of the reduced Venetian Platform includes Permian volcanism (Picotti et al., 1995).

In Oligo-Miocene, the undeformed and uplifting Euganei–Lessini swell and the NW striking Schio–Vicenza lineament acted kinematically as a lithospheric transfer system of the Southalpine flexuring. The inflection of the contiguous Venetian–Friulian sector was kept confined to the Serravallian–Messinian interval, and its additional Plio-Pleistocene deformation did not propagate further southwards in the Garda area. The evolution of the western Southern Alps shows activity along the Giudicarie system (Viganò and al., 2015; Viganò and al., 2008) and in its buried thrusts below the Po Plain (Livio and al., 2008).

From latest Messinian the structures of the northern Apennine margin and its frontal Plio-Pleistocene accretionary wedge became active on the southern side of the foreland by 2nd order arc and lateral ramp propagation geometries, driven by both the thrust belt eastward shortening increase and its Mesozoic compartmented heritage. In the constrained west Emilia sector larger detachments of the Neogene cover and rearrangements and cuts of the facing Southalpine folds ruled the accommodation (Fantoni et al. 2004), whereas to the east a larger spread of the accretionary system occurred (inner and outer Ferrara arcs).

In short, the studied area can be divided into two active domains:

1) the tectonic structures with a direction SW-NE in the Salò area (Michetti and al., 2004). The Rivoltella-Sirmione-Garda fault is situated on the bottom of the Lake Garda where they come from two hydrothermal sources, one is the Bojola source used by Sirmione spa, and has the same direction of Salò fault (Carraro et al., 1960; Rogledi 2013; Scardia et al 2015) that continues under the Po Plain in a E-W direction that perhaps caused the Brescia earthquake of 1222. Recently on the hill of Capriano del Colle (Bs) were found traces of recent strong earthquakes (Berlusconi and al., 2008). The convergence of these tectonic structures shows a zone of hedge to the circulation of fluids and could give a zone of NW-SE direction flow (read 3.3 Historical Earthquake in the Giudicarie-Lessini region);

2) the second domain is related to the Schio Vicenza fault system with two sub-vertical transfer faults: Nogara and Verona faults (Scardia et al., 2012, 2015). Mapping and kinematics of these faults is not fully understood, because they almost completely lay under the Plio-Quaternary cover, and

seismic reflection data do not allow a detailed structural characterization. The Nogara fault runs NW-SE from the Solferino thrust South of Verona (Rogledi, 2013). The existence of the Verona fault has been proposed long time ago on the basis of the alignment of hydrothermal and radioactive springs, and of the identification of a cataclastic belt recognizable in borehole stratigraphic logs (Zanferrari et al., 1982; Carton and Castaldini, 1985; Panizza et al., 1988; Serpelloni et al., 2005; Rogledi, 2010). Along this fault, a considerable drainage anomaly is present along the Adige River, which flows for several km against the mountain border without following the natural slope of the Po plain (Castaldini and Panizza, 1991). The Verona fault structure is NW-trending and runs through the city of Verona. The Quaternary deformation described in Sant’Ambrogio of Valpolicella for the Pastelletto Mountain thrust might instead be related to the Verona fault. However, there is no other site where the Verona fault can be studied in the field. Now the existence of both the Verona fault and Nogara fault structures has been proposed essentially based on geophysical and hydrogeological data (Berlusconi et al., 2013; Scardia et al., 2015).

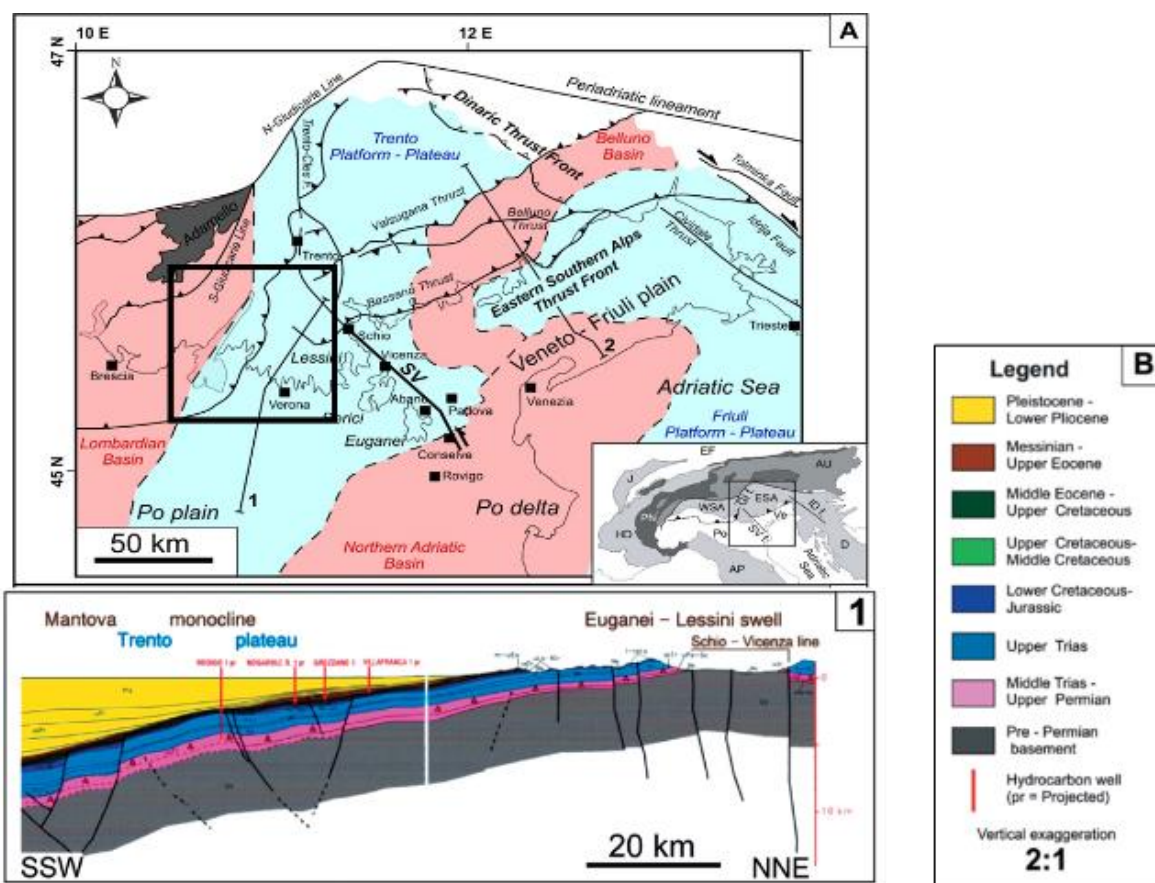


Fig. 3.3.4 Pola et al., 2014

- ✓ Simplified structural and paleogeographic map of north-eastern Italy (modified from Zampieri et al., 2003). The area is part of the independent Adria microplate and inherited a Mesozoic basin and swell architecture that controlled the subsequent Cenozoic Alpine compressional/flexural cycles. **A**
- ✓ The cross-section B1 across the Po Plain and Lessini Mountains (from Fantoni and Franciosi, 2008 and 2010) shows that the Lessini swell is unaffected by the shortening and represents an undeformed foreland block between the Central-Western and the Eastern Southern Alps. **B1**

### 3.3.2 The Lessinian block

The eastern study area is represented by the Lessini Massif and the related piedmont plain. The massif forms a monocline plateau with elevation increasing to the North reaching about 1800 meters. The plateau is carved by deep erosional valleys, N-S trending. From the morphotectonic point of view the plateau surfaces are controlled by tectonic structures, with the bedding of Mesozoic units dipping to the NW-SE in Western and NE-SW in Easter Lessinian Area.

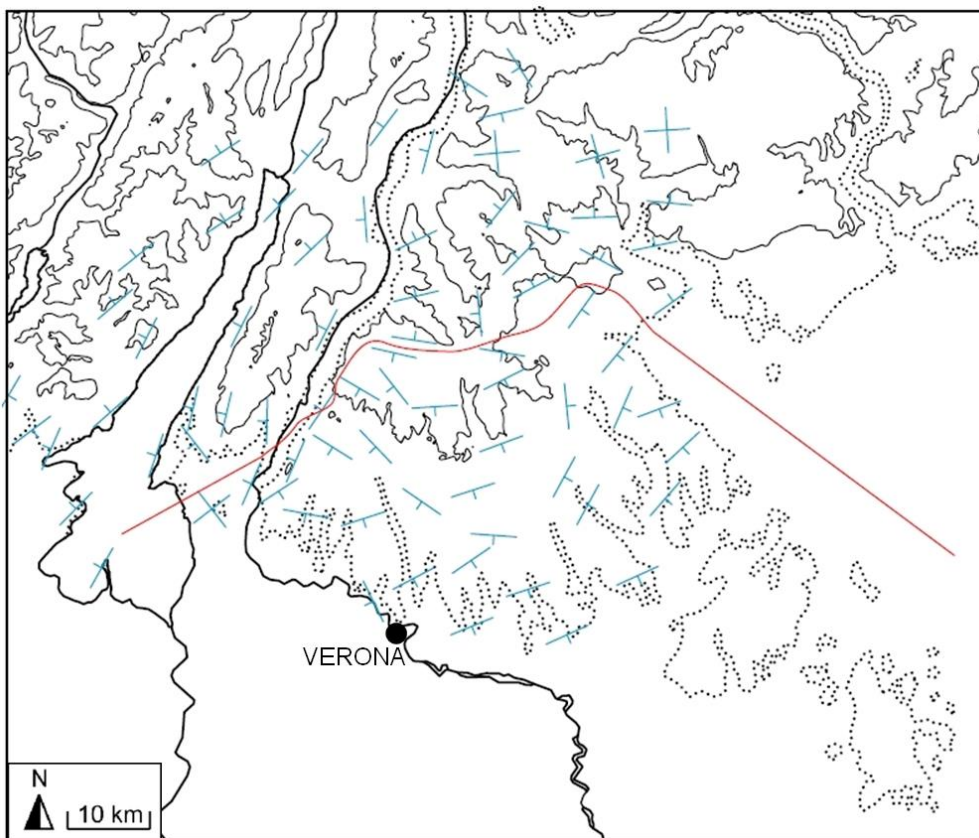


Fig. 3.3.2.1 Average trend of layer- slopes in the carbonate rocks of the Western Veneto-Southern Trentino involved in the recharge area of hydrothermal basin. The red line identifies the northern boundary of the lessinic monocline turned towards the plain (Scardia, 2012)

The direction of the major valleys coincide with high-angle faults related to tectonic grabens having a direction NW-SE (Bosellini et al., 1967). Many valleys show canyon-like profiles influenced by the lithology of the sedimentary rocks (Castiglioni et al., 1989).

Along the southern border of the Dolomites, the Giudicarie belt is structurally divided from the ENE to E trending Valsugana belt by the NW oriented Schio–Vicenza transfer fault zone. This fault separates also the western boundary of the Montello–Friuli belt to the East, from the Lessinian monocline to the West (Castellarin and Cantelli, 2000). The only slightly deformed Lessinian monocline, a southern extension of the Trento plateau, forms a triangular block between the frontal structures of the Giudicarie belt to the West and the Schio–Vicenza fault system to the East. It can be considered as an uplifted structural continuation to the N of the nearly tabular pedealpine monocline buried beneath the Po Plain (Pieri and Groppi, 1981). The geological setting of this sector was also dominated by the Paleogene basaltic volcanism and it differentiates the sub-volcanic bodies of the Euganei Hills in connection with strong extensional tectonics (Zampieri, 1995).

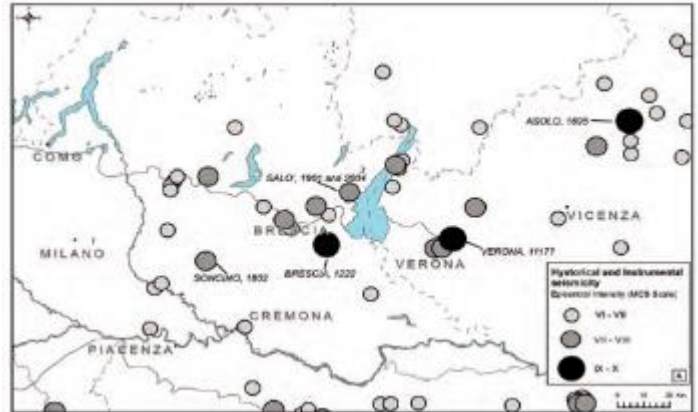
In the geological map of this area (Bosellini et al., 1967), the morphological characters are represented by valleys oriented like the major lessinian tectonic lines, from Schio-Vicenza fault (NNW-SSE) in the eastern area to the N-S and NNE-SSW directions, like Giudicarie belt, in western lessinian sector.

In the Lessinian massif the karst processes are marked by the development of deep caves into the carbonate Mesozoic succession (e.g., Spluga della Preta Cave, Ciabattino Cave and Tanella Cave; Zorzin et al., 2011). On the surface, the shape of the relief was controlled by the presence of volcanic bodies intercalated to the Cenozoic succession. In their correspondence the alluvial erosion acted more effectively than in the carbonates, giving the formation of large valley floors in the eastern area of the Lessini Massif.

### 3.4 Historical Earthquake in the Giudicarie-Lessini region

#### 3.4.1 Introduction

As we stated above, the Giudicarie-Lessini region is an important zone in the geodynamic context of the Alps (Fig. 3.1). It represents a primary discontinuity within the Southern Alps, with an orientation transversal to the strike of the Alpine chain. The low-to-moderate magnitude shallow seismicity of the Giudicarie-Lessini region is mainly located along this fault system, one of the most important seismic provinces in Northern Italy (Slejko et al., 1989).



#### 3.4.2 Seismicity and seismological databases

The Giudicarie-Lessini region was characterized by frequent low seismicity ( $MW < 5.0$ ), with moderate earthquake occurrence ( $MW \approx 5.0$ ; Pondrelli et al., 2007) in the period 1981-2002 (Chiarabba et al. 2005). The seismicity ( $M \geq 1$ ) is distributed along the Southalpine boundary (Castello et al. 2006) (Fig. 3.2), as confirmed by historical seismicity until 1980 (Gruppo di lavoro CPTI, 2004) (Fig. 3.1.3 and Table 3.1). In the internal chain, a seismic area is recognized north of the Periadriatic

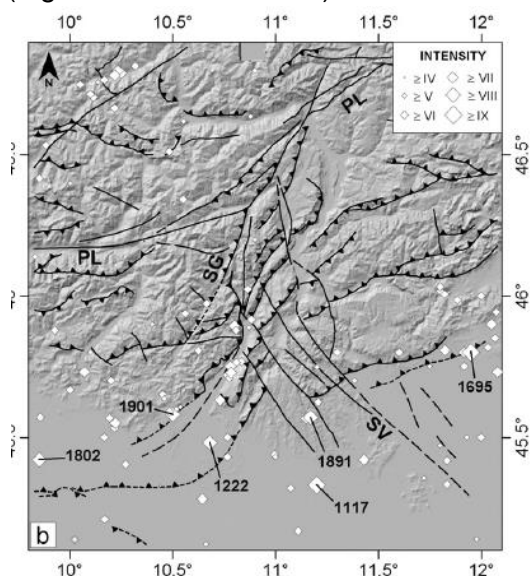


Fig. 3.4.2.1 – Historical seismicity of the Giudicarie – Lessini region with most intensive earthquake. Epicentral intensity (I) is expressed in the MCS scale (Viganò et al., 2015 left and Berlusconi et al., 2013 right)

Lineament in the Swiss Alps. The seismicity in the Giudicarie-Lessini region is clustered near the junction between the Giudicarie and the Schio-Vicenza fault systems and decreases in frequency and magnitude away from this junction in EW direction (Fig. 3.1.4). Most earthquakes are located in the upper crust ( $z < 20$  km;

Scarascia and Cassinis, 1997; Cassinis and Solarino, 2006).

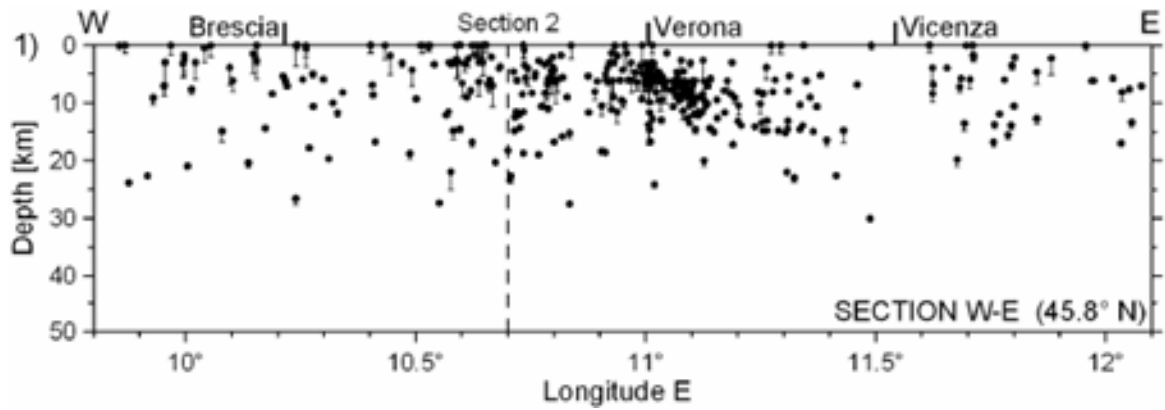


Fig. 3.4.2.2 EW cross section with seismicity (1981-2002) of the Giudicarie-Lessini region (Viganò, 2015)

Table 3.4.2.1- Some most intensive historical seismic events of the Giudicarie-Lessini region (see Fig. 3.1.3 - Gruppo di lavoro CPTI, 2004). Epicentral intensity (I) expressed in the MCS scale, Viganò, 2015, modified.

ID	Date [yy/mm/dd]	Time [hh:mm]	Lat [°]	Long [°]	Area of Maximum effects	I
a	1117/01/03	13:..	45.33	11.20	Verona Area	IX/X
b	1891/06/07	01:06	45.57	11.17	Illasi Valley	VIII/IX
c	1222/12/25	11:..	45.48	10.68	Southern Brescia Area	VIII/IX
d	1901/10/30	14:49	45:58	10.50	Salò	VIII

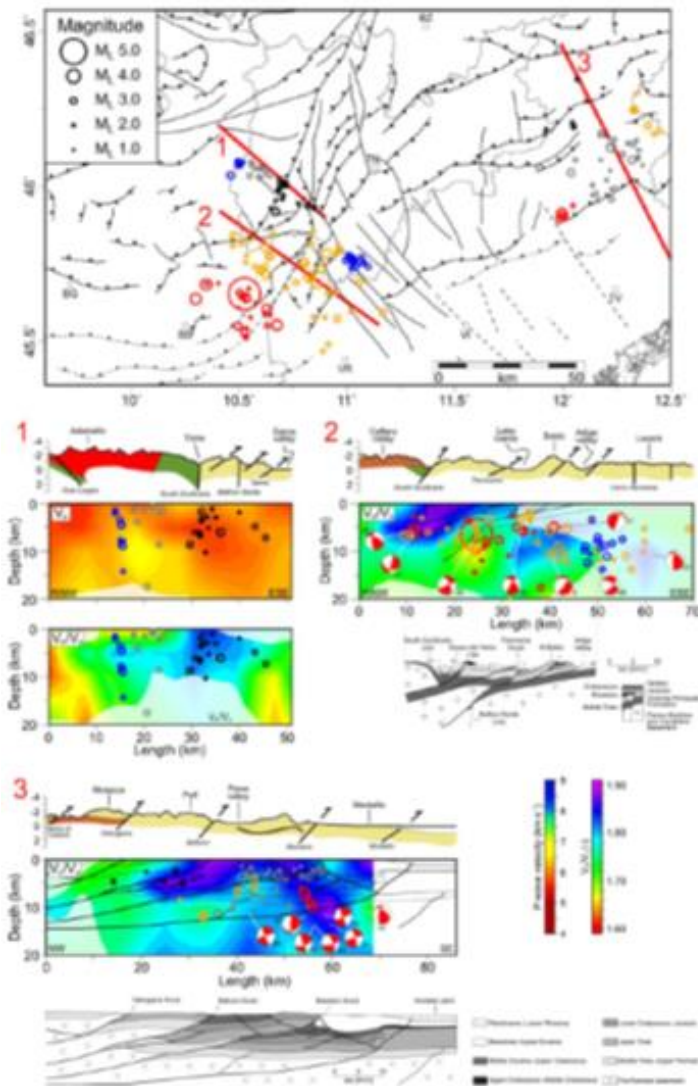


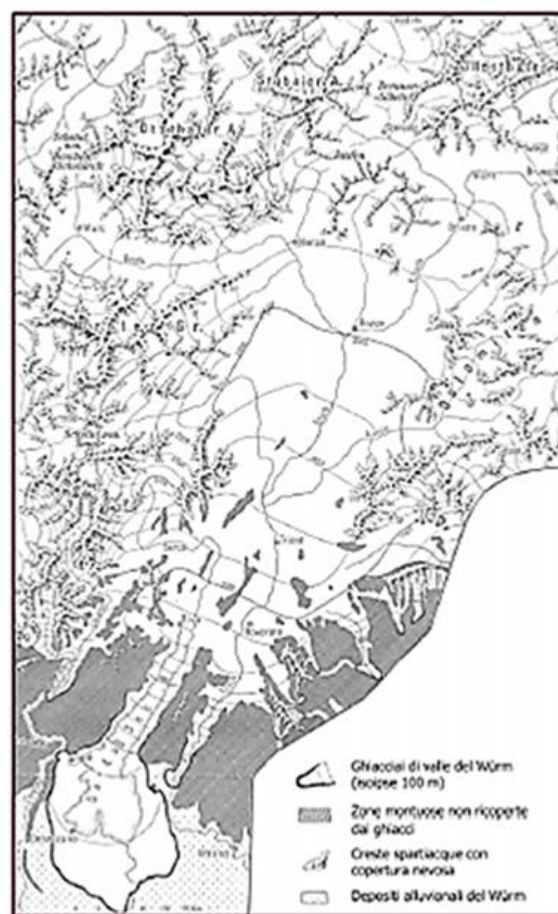
Fig. 3.4.2.3 Cross sections with focal mechanisms (see Table 1) relevant geology and faults, and crustal tomography (from Viganò et al., 2013 and 2015). Sections shown (1, 5 x vertical exaggeration). Coloured circles identify earthquake clusters plotted on each cross – section (Viganò et al., 2015).

In studied area some faults show activity (see Zampieri, 1995; Sauro and Zampieri, 2001) preferential pathways for thermal activity.

### 3.5 The Plio-Quaternary stratigraphy of the Garda Area

The Lake Garda (65 m a.s.l.), the largest lake of Italy, is hosted in a NE-SW basin cut through the sedimentary cover of Southern Alps, which includes the occurrence of volcanic bodies and dykes. As we saw above this part of the Southern Alps was deformed in form of an asymmetric syncline, trending NNE-SSW, and thus dissected by thrusts (Castellarin and Cantelli, 2000; Castellarin et al., 2005).

Fig. 3.5.1- The historical reconstruction of the North-East area during the last glacial “Würm” maximum (modified from Castiglioni 1940 and Pencck and Bruckner, 1909).



This structure controlled the development of the main drainage axes of rivers and glaciers.

The Pliocene – Early Pleistocene remnants are scarce and scattered in the area (Scardia et al., 2015); however they suggest the presence of marine embayment close to the Garda (Scardia et al., 2006) till the onset of the major glaciations (Muttoni et al, 2003). The main Pliocene

succession are at San Bartolomeo di Salò and Sant’Ambrogio Valpolicella.

*The conglomerate of San Bartolomeo* (San Bartolomeo Hill-Salò) stands on the western bank of Lake Garda and represents a classic site of the Alpine geology, chiefly consisting of faulted Pliocene marine clays, uplifted to an elevation of ~500 m. According to Picotti et al. (1997a) the San Bartolomeo deposits appear to be deformed by three distinct events: the older one is compressional and, it is followed by two younger extensional phases, similar to those ones recorded in the Monte Orfano Conglomerate. The San Bartolomeo Hill succession is traditionally referred to span Messinian to late Pliocene (e.g. Baroni & Vercesi, 1995; Picotti et al., 1997a), but dated later early Pliocene (Scardia et al., 2010; 2015).

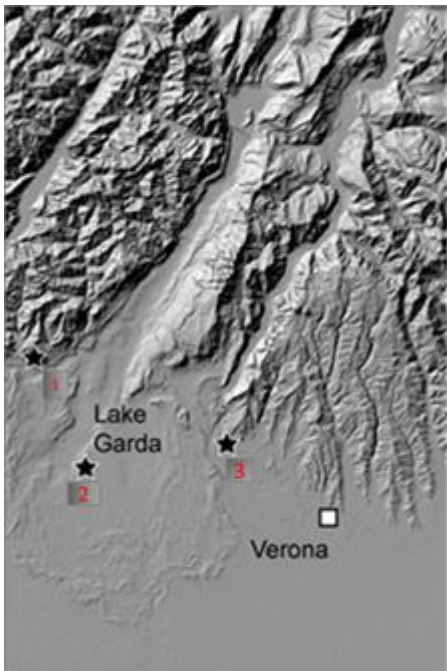


Fig. 3.5.2. - Location of conglomerate sites: 1) San Bortolomeo Formation; 2) Sirmione Conglomerate; 3) Montecio Conglomerate (Scardia et al., 2010 modified).

The *Montecio Conglomerate* is exposed at S. Ambrogio di Valpolicella and along the Cà Verde depression. The conglomerate rests with an erosional lower boundary on the bedrock and develops with horizontal and planar cross-bedded, well-sorted, well-rounded, fine-grained gravels. Upward, clast size increases up to 25-30 cm and conglomerate is crude-bedded. The succession ends with several, superimposed gravel to sand fining-upward cycles. The overall thickness is ~50 m. Sediment petrography is composed by limestones, dolostones, and few clasts from volcanic and metamorphic rocks. The facies observed in the Montecio Conglomerate can be all interpreted as deposited by a shallow, gravel bed, braided river. The good organization of the body rules out a deposition by a local stream, but rather points to a deposition in a braidplain with local high-energy episodes.

According to the petrographic composition the provenance of the Montecio Conglomerate can be constrained to the Valle Lagarina, with likely a very small contribute by the Val Sugana basement. Dating the Montecio Conglomerate is a hard task due to the complete lack of fossils and fine-grained layers suitable for pollen and paleomagnetic analyses. According to field geology, petrographic, and geomorphologic considerations, the Montecio Conglomerate must be older than Middle Pleistocene. Tectonic deformation of the Montecio Conglomerate has been recognized since a long time (e.g. Cozzaglio, 1933). Pebbles are heavily pitted and the conglomerate is frequently fractured. Faults have been reported by Castaldini & Panizza (1991). From the geologic survey at least two fault zones have been detected in the Montecio Conglomerate (Scardia et al., 2015). Both fault zones are characterized by a sub-vertical belt of unconsolidated clasts in fine-grained matrix and calcite mineralizations. The fault planes are generally sub-vertical with an E-W trend. The best case, observed along the road from S. Ambrogio to Montecio is 2°/70° (Az/Dip) oriented and can be interpreted as an extensional feature, filled by slope deposits (Fig. 9). Clasts show in few case

horizontal striations, ascribable to strike-slip kinematics. The Cà Verde depression has been interpreted as a fault zone by Cozzaglio (1933) and the staircase distribution of the Montecio Conglomerate along the NE bank of the depression may suggest a tectonic origin for the depression, filled by organic-rich lacustrine/swamp deposits and sealed by slope deposits (Venzo, 1961). Cà Verde depression returned homininid cranium remains and paleolithic artifacts (Brunetto & Chelidonio, 1989), suggesting that the depression was already formed at least since ~200 ka. The observed tectonic deformation cannot anyway easily constrained in time. A Pliocene age was determined by Scardia et al. (2015).

At the onset of the major Alpine glaciations, in the late Early Pleistocene (Muttoni et al., 2003), the Garda basin was reached several times by Alpine glaciers from the Adige catchment; these bearing crystalline rocks (porphyries, metamorphic and granitoids) from the volcanic platforms and the crystalline axial belt of the Alps (Baroni and Cremaschi, 1987; Garzanti et al., 2011). Multiple Middle and Late Pleistocene glacial advances spread on the southern Alpine border with a large piedmont lobe, the biggest in the southern Alpine side (Castiglioni, 1940; Ehlers & Gibbard, 2011). The age of the moraines of this typical composite end-moraine system, including the minor system of Rivoli Veronese related to the Lagarina valley, has been intensively debated (Penck and Brückner, 1909; Venzo, 1965; Habbe, 1969; Cremaschi, 1987; Accorsi et al., 1990; Bini and Zuccoli, 2004; Ferraro, 2010).

The western area of the present study is located the morainic amphitheatre of Lake Garda corresponding to a hilly landscape made up of the terminal moraine complex of the Adige-Sarca paleoglaciers. Most of the glacial deposits can be ascribed to the late Pleistocene (Cremaschi, 1987; Ravazzi et al., 2014).

Glacial remnants belonging to the Early and Middle Pleistocene are preserved to the west, near the Chiese River, from Salò to the Ciliverghe hill to the South (Cremaschi, 1987). The piedmont plain corresponds to the outwash plain (sandur) of the Upper Pleistocene deposited by the spills of the Garda glacier (Baroni and Cremaschi, 1987; Cremaschi, 1987). The outwash plain is terraced by streams of Alpine and Prealpine origin such as the Chiese, Mincio Rivers. In this context important

is dated the conglomerate present in lake area. The series of quaternary deposits is heterogeneous and can be divided in continental and marine units (Venzo, 1965). We can see in figure the sequence of moraines and conglomerates with thickness of 90-100 m related to the eastern sector of the end-moraine system (in figure sequence of Valle dei Mulini with 90 meters of thickness).

In this perspective it is peculiar the conglomerate body of Sirmione, which represent the first glacial deposit documented in the central Garda, and can be compared to those present in the western sector. (Photo of section Sirmione conglomerate).

*The Sirmione Conglomerate* is located in the middle of the Lake Garda, the north end of the Sirmione peninsula is an isolated relief consisting of late Cretaceous cherty and marly limestones (Cita, 1949), unconformably overlaid with conglomerate and sparse glacial deposits. The Sirmione Conglomerate is preserved in the south-eastern sector of the peninsula and has been attributed to the Late Miocene (e.g. Carraro et al., 1969) as well as to the Middle Pleistocene (Cremaschi, 1987). Extended outcrops are common along the eastern bank of the Villa Cortine hillock (Sirmione), where the main studies were carried out by Scardia et al. (2015). Elsewhere around the Villa Cortine hillock, conglomerate outcrops are limited and scattered. The Sirmione Conglomerate lies with a high-angle erosional



boundary on the bedrock and is composed by two members, reported as follows from Scardia et al. (2015).

**Lower member.** The lower member consists from the bottom of massive, coarse-grained, matrix-supported gravel, with boulders from angular (limestones) to rounded (porphyries) shape, passing upward with an erosional surface to a crudely-bedded conglomerate, sealed by massive to laminated fine-grained deposits with sandstone lenses. Crystalline rocks are strongly weathered, the fine-grained layer has a lateral continuity of several tenths of meters. The transition to the upper member is characterized by a 5-6 m-thick, crudely bedded, clast-supported conglomerate, showing better sorting, rounded clasts and a remarkable minor amount of porphyries. Facies association points to a deposit characterized by longitudinal bars and thick debris flow deposits with boulders and blocks up to 1 m size, suggesting a very proximal outwash plain depositional settings, passing upward to braidplain shallow, gravel-bed river channels. Petrographic composition show high amounts of

The Sirmione Conglomerate

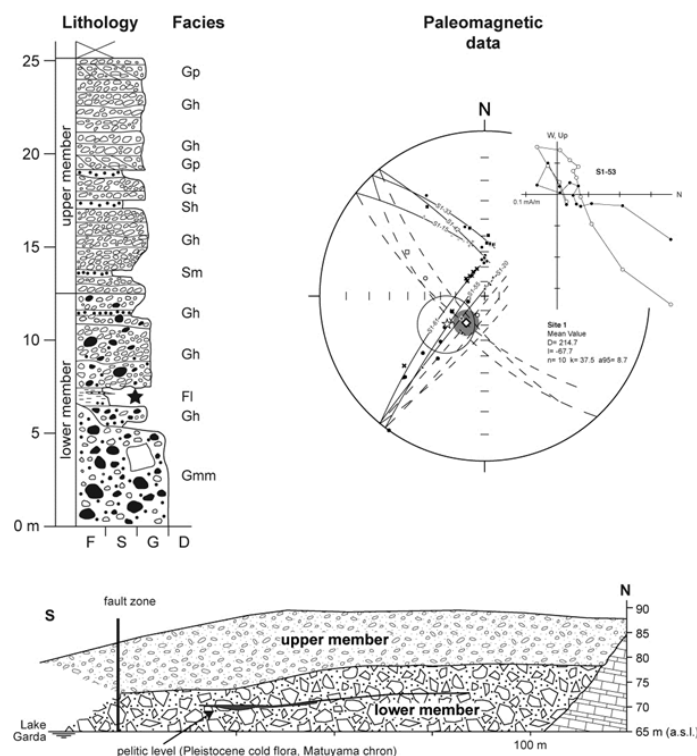


Fig. 3.5.3 - Stratigraphy (left), facies, paleomagnetic data (right), and geological section (bottom) of the Sirmione Conglomerate. Star in the stratigraphic plot indicates the pelitic level studied for paleomagnetism and pollen (Scardia et al., 2010; Scardia et al., 2015).

volcanic and metamorphic rocks from the Southern and Central Alps. At the whole, the lower member of the Sirmione Conglomerate has an observable total thickness of 11-13 m.

**Upper member.** The upper member is composed by horizontal to planar cross-bedded conglomerate, well-sorted and clast-supported. Laminated to massive sandstone lenses occur, more frequently towards the top. Very rare fine-grained layers are thin and observed at the top of sandstone lenses. The dominant facies association are interpreted as a vertical stack of shallow, gravel-bed river channels, pointing to a braid plain depositional system. Sediment petrography consists of limestones (mainly oolitic), dolostone, and chert. The average thickness is of 12-15 m, but in the northernmost outcrops the conglomerate lies on the bedrock.

In detail, the lower member shows a very high content in quartz, volcanic, metamorphic, and dolostone rock fragments, pointing to the Adige drainage basin. On the other hand, the upper member is characterized by high content in sedimentary rock fragments (>90%). The occurrence of cherts, biocalcarenites, and oolitic limestones points to a source area corresponding to the present-day Valle Lagarina and the southern slope of the Monte Baldo. A western provenance is less likely, because it should produce a higher occurrence of dolostones, which widely crop out in this area. Conversely, the occurrence of oolitic limestones, which are characteristic of the Jurassic Trento Plateau (e.g. San Vigilio Oolites), strengthened the hypothesis of a north-eastern source area. The provenance change can be ascribed to a switch between glacial to interglacial conditions, when, with the retreat of the glacier, local rivers exploit the abandoned outwash plain (Scardia et al., 2015). The facies of the lower member strongly suggest a glacial setting, which constrains the Sirmione Conglomerate to the late Matuyama (0.99-0.78 Ma) (Scardia et al., 2015).

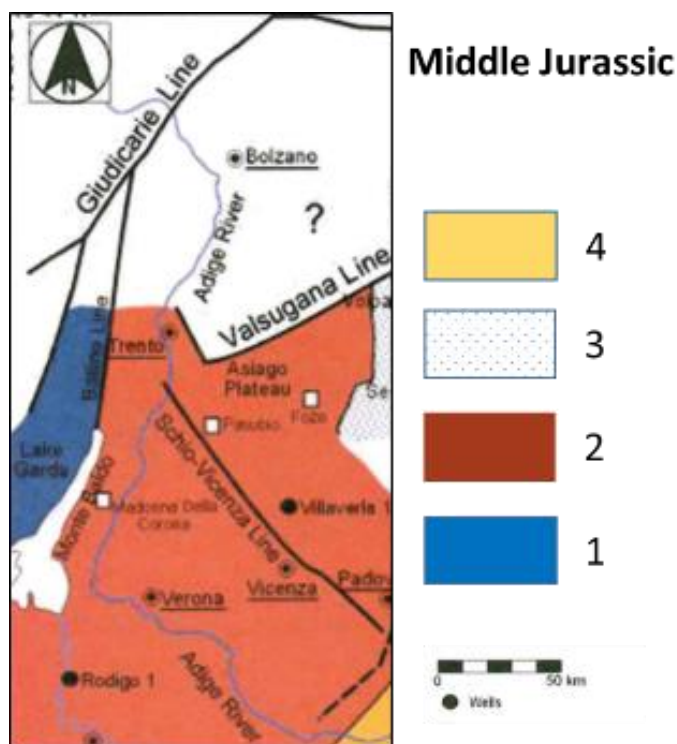
The subsequent glaciations shaped the Lake Garda valley and morainic system, whose morphology marks a not concentric spatial pattern of the morainic ridges that can be ascribed to a counterclockwise rotation (Cremaschi, 1987). In the morainic system the deposits related to the Last Glacial Maximum (LGM onwards) spanning from 30 to 18 ka cal BP (Schaefer et al., 2006; Lambeck et al., 2014) are the more extended and well-preserved (Cremaschi, 1987). Here the morphology of

the glacier withdrawal phases of the last glaciation are maintained and formed several sedimentary archives documenting the de-glacial sequence (Ravazzi et al., 2014).

Loess deposits are documented in the eastern area of Verona where, from some recent diggings in Caldiero, it was possible to examine the dolomitic content (Meneghel, 1990). In Cremaschi et al. (1987) the dating of humic fraction in loess in the Val Sorda sequence (moraine system of the Garda area) allows to know the period of sedimentation area that took place during older cold arid phase of the Wurm glacial period.

### 3.6 Hydrogeology of the area

The hydrogeology of the area can be divided in two units: a high plain with very permeable alluvial



sediments covering fractured and a low plain with clay, silty clay, sand and gravel layers.

The pre-Alpine areas, where groundwater flows in major hydraulically connected vertical and horizontal fracture zones, have high hydraulic conductivities and considerable dimensions, feeding the porous alluvial aquifer by hardly detectable pathways in the subsurface (Pilli et al., 2012).

Fig. 3.6.1 – Middle Jurassic paleogeography. 1) deep-water deposits of the Lombardian Basin; 2) condensed deposits of the Rosso Ammonitico Veronese (lower member); 3) resediment oolitic deposits of the Vajont Limestone; 3) deep-water deposits of the northern Adriatic Basin (modified by Masetti et al., 2012).

The regional aquiclude is represented by the metamorphic rocks of the pre-Permian crystalline basement that has been reached by hydrocarbon exploration, "Villaverla1" at a depth of 4200 m (Fig. 3.4.1). Middle Triassic succession composed of a great variety of rocks such as sandstones, evaporates, limestones, marls, siltstones, dolomites. The main karstic hydrogeological unit is represented by the Middle-Late Mesozoic which was characterized at the base a dolomitic platform (DP-Dolomia Principale Fm., Carnian-Norian), above Calcari Grigi Formation, a neritic carbonates of liassic age, oolitic carbonates and marls (Fig.3.4.2). At the end of Mesozoic age, Cretaceous, a variety of pelagic sediments, mainly compact to nodular micritic limestone, with millimetric marly to clayey interstrata, and summing up various different formation is evident.

Between the end of the Cretaceous and the Paleocene the wide pelagic basin was divided in horsts and grabens causing somewhere a partial lack of deposition or the sedimentation of micritic marly limestones. During the Eocene and Oligocene the area experienced a shallow water sedimentation represented by limestone and marly limestone with terrigenous sediments such as the Priabona and Calcarenite di Castelgomberto Fms. Some areas were subjected to thick deposition of basic volcanics, above all basalts and tuffs, due to the formation of quickly drowning grabens.

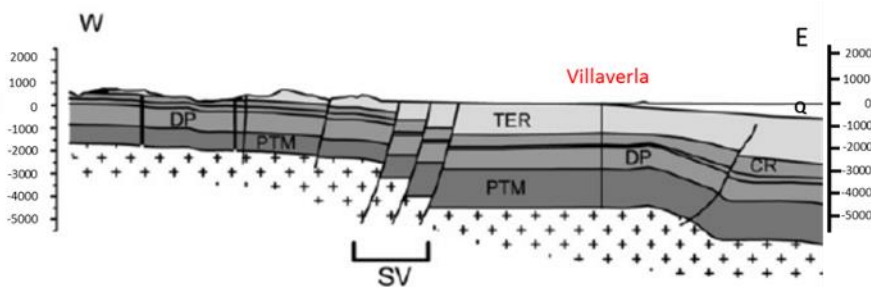


Fig. 3.6.2 – Geostructural cross section modified. E-W cross section highlighting the tectonic structure of the investigated area. In the section deep well of Villaverla (VI). The horizontal and vertical scales are the same.

### 3.6.1 Fault and Permeability of the rocks

The structural architecture of faults, and their resulting permeability structure and aquifer development, are strongly controlled by rock type (Bense et al., 2013).

<b>HYDROGEOLOGICAL UNIT</b>	<b>HYDRAULIC CONDUCTIVITY</b>
<b>Q</b> <b>Quaternary</b>	High (Porous Aquifer)
<b>CR</b> <b>Tertiary</b>	Low (Fractured Aquitard)
<b>DP</b> <b>Upper Trias-Cretaceous</b>	Very High (Karstic Aquifer)
<b>PTM</b> <b>Permian-lower Trias</b>	Low High (Fractured Aquifer/Aquitard)
<b>Prepermian Basement</b>	Very Low (Fractured regional Aquiclude)

A first-order description of fault zones commonly includes a fault core, which is surrounded by a damage zone. The fault core, as the zone of the most intense strain, is generally found in the center of the fault zone, and accommodates the majority of the displacement within the fault zone. The damage zone has secondary structures such as fractures, and minor faults extending into the foot-wall and hanging-wall, which take up the remainder of strain within the fault zone. In unlithified sediments, in which mixing of sediments can occur in the fault zone, an additional zone, called the 'mixed zone' exists in between the damage zone and the fault core (Heynekamp et al., 1999).

While dissolution weathering often dominates carbonate rocks, primary fault deformation mechanisms in fine-grained carbonate rocks, often have low primary porosity but fracturing and subsequent dissolution can cause large enhancements of permeability resulting, in carbonate rocks, often being considered aquifers or reservoirs. More than in any other lithology, faults cutting through carbonate rocks will often be dominated by secondary dissolution and precipitation processes altering the permeability structure almost continuously. Springs and outflows often occur along faults in carbonate rocks. An example of a fault related thermal spring emerging from carbonate rocks is the Bath hot spring in southwestern England (Andrews et al., 1982) or, in this studied area, the Sirmione hot spring in Lake Garda and the Caldiero warm spring in Verona Province. These springs

have been interpreted to represent emerging flow from within the fault zone itself, implying that the fault zone acts as a conduit (Billi et al., 2007) or below the fault zone implying that the fault zone acts as a barrier (Giurgea et al., 2004; Celico et al., 2006).

## CHAPTER 4

### *Historical Outline*

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The historical outline is very interesting. During the Roman Period the warm-hot springs were already known and, perhaps, utilized such as thermal bathrooms. Sirmione and Caldiero show remains of buildings and artefacts of villas near these sources. As regards Caldiero we have news and documents on the springs since early years of the fifteenth century while for Sirmione the thermal spring had a resurgence in the nineteenth century after excavation that put in evidence the presence of the roman domus. Even more recent is the knowledge about other thermal events of the studied area. In 1797, in the locality of Domegliara, western Verona a well was dug that temperature was over 40 °C.

In 1898, Camillo Negri and Enrico Nicolis, in a script about Veronese waters wrote: "...la fonte termominerale di Domegliara (43°C) si mantiene a 67 m sotto la superficie, ed invece quella di Caldiero (27 °C) super ail suolo".

In 1936, Giovanni Bragagnolo, analysed the water of Villa Zurla in Domegliara and put in evidence a similarity to those of Caldiero in both the chemical composition and in the tectonic structure, but none likeness with Sirmione water.

Some researchers, Sighinolfi, Gorgoni, Martinelli, Sorbini, did a research for CNR, on the thermal system Veronese, especially on thermal area of Caldiero (see studied case).

At that time a new research was carried out in Lazise area, indeed thermal water of 42°C in Thermal Garda Park (Villa dei Cedri in Colà) are utilized. In fatc there is in this site a place called "Caldane".

In the Veronese coast of Lake Garda there is a thermal anomaly with temperatures among 22-25 °C.

Now a new spa exploits the thermal anomaly of Western Veronese area. This spa was built in a place called “Fossa Fumara” showing that the old place names gave correct information about temperature of leaving water.

About the thermal water of Veronese area were not written many books, but I would like to mention a book published in 2012 at Museo di Storia Naturale of Verona entitled “Acque calde e geotermia della Provincia di Verona”, a popular text on the subject.

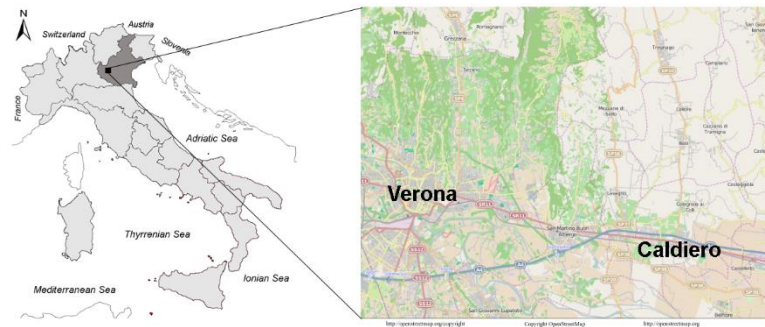
### *The History of Juno spa*

The studied thermal “spa” of Caldiero is an area of about 10 km<sup>2</sup>, located in the North-Eastern part of Italy, between the Adige River at the south and the Lessini Hills at the north (Fig.6.1). The site was known in ancient Roman times as ‘Calidarium’, stemming from its thermal baths from IV century A.C.



The word ‘spa’ may be derived from the Wallon word ‘espa’ meaning fountain, but also from the Latin word ‘spagere’ (to scatter, sprinkle, moisten) or, perhaps, an acronym of the Latin phrase ‘sanitas per aquas’ (health through water). In Britain, the word spa is still used, while in Europe the term ‘thermal water’ is preferred (Tubergen and Linden, 2002).

The thermal water of Juno is situated in Caldiero, little eastern town of Verona (Fig.4.1).

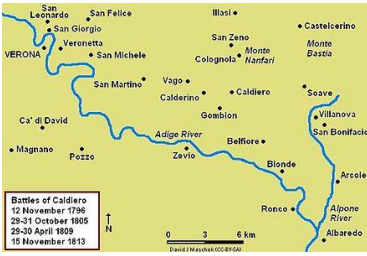


The history of Baths of Caldiero is complicated. It is assumed that these waters were known already from *Paleoveneti*. After Roman dominium the Baths were dropped to then be reevaluated in 1458 by resolution of Verona Municipality '*pro balneo de Caldiero redigendo et reformando*'. In this time many academics wrote about the Baths of Caldiero like Giovanni Antonio Panteo, in "*De thermis caldjaranis*" (read also "*I bagni di Caldiero*" Chiecchi and Lupi, 2012) or many others as Boldiero (1473), Fallopio (1571). Between 1567 and 1589 Ventura Minardo da Este, Camaldolese father, analysed the thermal water and his historical and scientific observations are very important for us. Minardi in "*De balneis Calderii in agro Veronensi*", Venezia 1571.

The studies of Minardi are interesting above all the description of the chemical techniques used to analyse the thermal water.

In 1795 two Veronesi doctors, Matteo Barbieri and Zenone Bongiovanni, wrote "*Illustrazione delle terme di Caldiero nel distretto veronese*" after newly reissued by Accademia dell'Agricoltura e delle Scienze of Verona, a significant work with illustrations and comments about therapeutic powers of Juno thermal water.

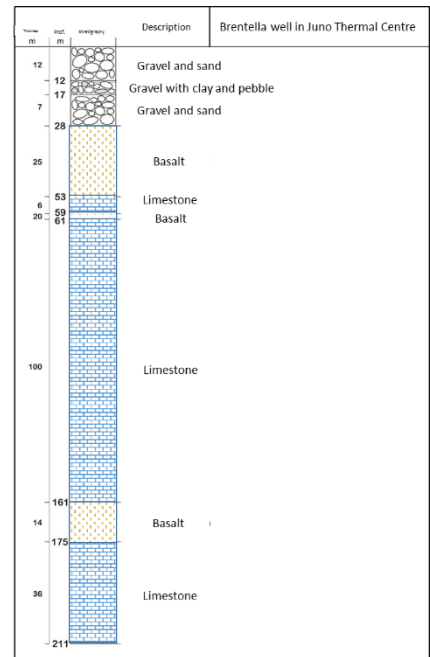
In this book the authors described their reflections about origin of the thermal water that we can sum up so: "*L'acqua decomponendo nel sottosuolo il basalto e il tufo calcareo, di cui erano costituite le rocce, si appropriava dei loro componenti. Questi disciolti nell'acqua reagivano fra loro liberando il calorico durante le reazioni chimiche esotermiche*".



Between 1796 and 1813 in Caldiero were fought a lot of battles and the Juno thermal Centre fell into ruin. In 1864 Municipality of Verona

entrusted to Castelli doctor the task to publish a book entitled “Le antiche terme di Giunone in Caldiero: cenni storico-medici sulle medesime”.

In the middle of XIX century railway “Ferdinandea” was built by Austrian government. The railway stretch in Caldiero crosses a trench dug along the slopes of M.te Gazzo, at North-West of the thermal Baths. This trench is very interesting to observe the sequence of basaltic lavas with the limestones of the Tertiary age.

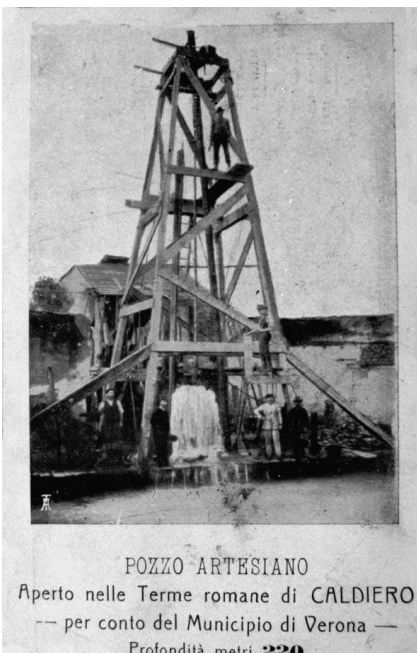


In 1911 was built a well of 220 meters of deep (photo and stratigraphic sequence).

Sighinolfi et al., in 1982 wrote an important article about the waters of thermal Veronese system.

In this article were analysed thermal water of Caldiero and some samples of aquifer water also of the Verona Province (see chapter 4 paragraph 4.7).

In 1986 was built another well called Olimpia deep 79 meters.



In two thesis, Cazzola (1986) and Compagnoni (1991) - University of Padua, we can see the data of some water wells.

Further geological and hydrogeological research was carried out by a geologist, Maria Frigo Sorbini, in 1990. In this technical investigation she wrote the rainwater drop to thermal basin from Piccole Dolomiti and Lessini Mountains, crossing geological layers in the depth, where get warm, forming a geothermal circuit that is housed in a deep carbonate reservoir. The water runs in

depth and goes back when it meets fractures of bedrock above the Baths of Caldiero.

This water has chemical similar characteristics to Euganei-Berici water (Piccoli et al., 1973; Sighinolfi and al., 1982; Frigo-Sorbini, 1990).

#### *“Boiola or Bojola” spring Study*

A hydrothermal spring is present on the eastern side of the peninsula of Sirmione: Boiola spring (see Photo Google earth above). The history of Boiola is very interesting. In 1887 Piatti A. wrote: “E’ generalmente noto che a levante della penisola di Sirmione, quasi di fronte alle rovine dell’antico palazzo romano (see Orti-Manara, 1856), dette le grotte di Catullo, a circa 170 metri dalla spiaggia scaturiscono continuamente da parecchi punti del fondo delle bolle in gran numero e talor molto grandi, che vengono a scoppiare alla superficie, diffondendo intorno odore di acido solfidrico....E’ noto anche che l’acqua del fondo ha una temperatura elevata in certi punti; che perciò questo efflusso di bolle, che gli abitanti del luogo chiamano la Boiola, è l’effetto di una sorgente termo-solforosa, che scaturisce dal fondo...”. Piatti told about five points where the bubbles rise. Always prof. Piatti, in a missive to ing. Zezi on ‘Bollettino del Reale Comitato Geologico’ wrote: “...onde fu stampato che la distanza di essa (la Boiola) dalla spiaggia è di 170 metri, mentre è di 270 metri



all'incirca e varia secondo il livello del lago...". In 24 August 1889, a Venetian diver man, whose name was Procopio, equipped with a diving suit and special pumps that he had brought over from Great Britain, descended 20 meters into Lake Garda and arrived at the Boiola hot water spring. After several attempts, he inserted a long pipe into the rocky stratum, from which poured hot sulphurous water. Afterwards there was a long and delicate process of channeling to carry on the coast the thermal water with about 300 meters of metal pipes (photo 4.1).

Then the doctor Luigi Biasi analysed water of spring: "Acido Solfidrico molto abbondante, Acido Carbonico libero, tracce di Carbonati, tracce di Solfati, Solfato di Magnesia, Solfato di Soda, Solfato di Ferro, tracce di ioduri, tracce di tannino".

Many wrote about Boiola spring and analysed the water such as Chimelli (1890), Negri and Nicolis (1890), Tosana (1890), Tosana and Anselmi (1890), Lombardi and Piatti (1891), Da Vico (1901), Massalongo (1902), Ferrara (1910), Monti (1913), Brentari (1914), Porro (1922), Pinali (1923), etc. Cita Maria Bianca, in 1949, described the Sirmione peninsula in 'L'affioramento Neocretaceo di Sirmione e la sua Microfauna' and, towards the end of the article pointed out: "esiste a Sirmione una sorgente termale solforosa chiamata Bojola, che sgorga dal fondo del lago in un punto situato circa 300 m ad E delle Grotte di Catullo...la sorgente della Bojola non è l'unica, ma altre ne scaturiscono dal fondo del lago...esse risultano disposte lungo una linea diretta da SO a NE..". The observations continue highlighting the faults present in the studied area.

According to some authors the origin of spring water thinks to derive from Mount Baldo which acts as a watershed in this area. In this research instead, chemical and isotopic analysis would give an origin far more away of this water.

The collected data show that all the structures in the Lake Garda area have been active during Middle Pleistocene to Holocene, and this activity is underlined by a diffused historical and instrumental seismicity (Berlusconi et al., 2013), but relations between strong seismic events and specific faults, which are the possible cause of powerful earthquakes, are still unclear.

The Quaternary seismicity gave rise to hydrothermal spring whose chemistry and isotopic origin is closely related to tectonic activity in this area.

The chemical and isotopic characteristics of the thermomineral water of Boiola highlight a farther origin than thought and that deepens, due to the present faults, up to emerge near the coast of peninsula of Sirmione. Further analysis are necessary to obtain a more complete model of water circulation and thermal water basin recharge.

# CHAPTER 5

## *Hydrogeochemical surveys*

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### *5.1 Introduction*

Hydrogeochemical investigation is the set of activities leading to the knowledge of the chemical-physical, chemical and isotopic characteristics of water. By means of these surveys is possible to achieve useful information about the water quality, presence of different components that feed a water body and their interactions, processes and mechanisms that affect the water quality and the hydrodynamic behaviour of groundwater, arrangement of groundwater flow paths, etc.

In respect of the aims of this Thesis, some sampling fields were carried out in order to analyse concentration of chemical compounds (principal, minor and traces) and isotope signatures, both for water ( $\delta^{18}\text{O}\%$ ,  $\delta^2\text{H}\%$  and  $^3\text{H}$ ) and some solutes (S and Sr).

The main objectives of these activities have been:

- to recognise the main hydrothermal flow systems and their possible interactions;
- to define the recharge areas and the groundwater flow path of such systems;
- to estimate the temperatures reached by the fluids at the equilibration zones at depth;
- to evaluate the relationship among the hydrothermal systems and the aquifers hosting fresh water.

Both for the planning of sampling activities and the interpretation of analytical results, the geological and hydrogeological framework and geochemical data from literature were taken into account.

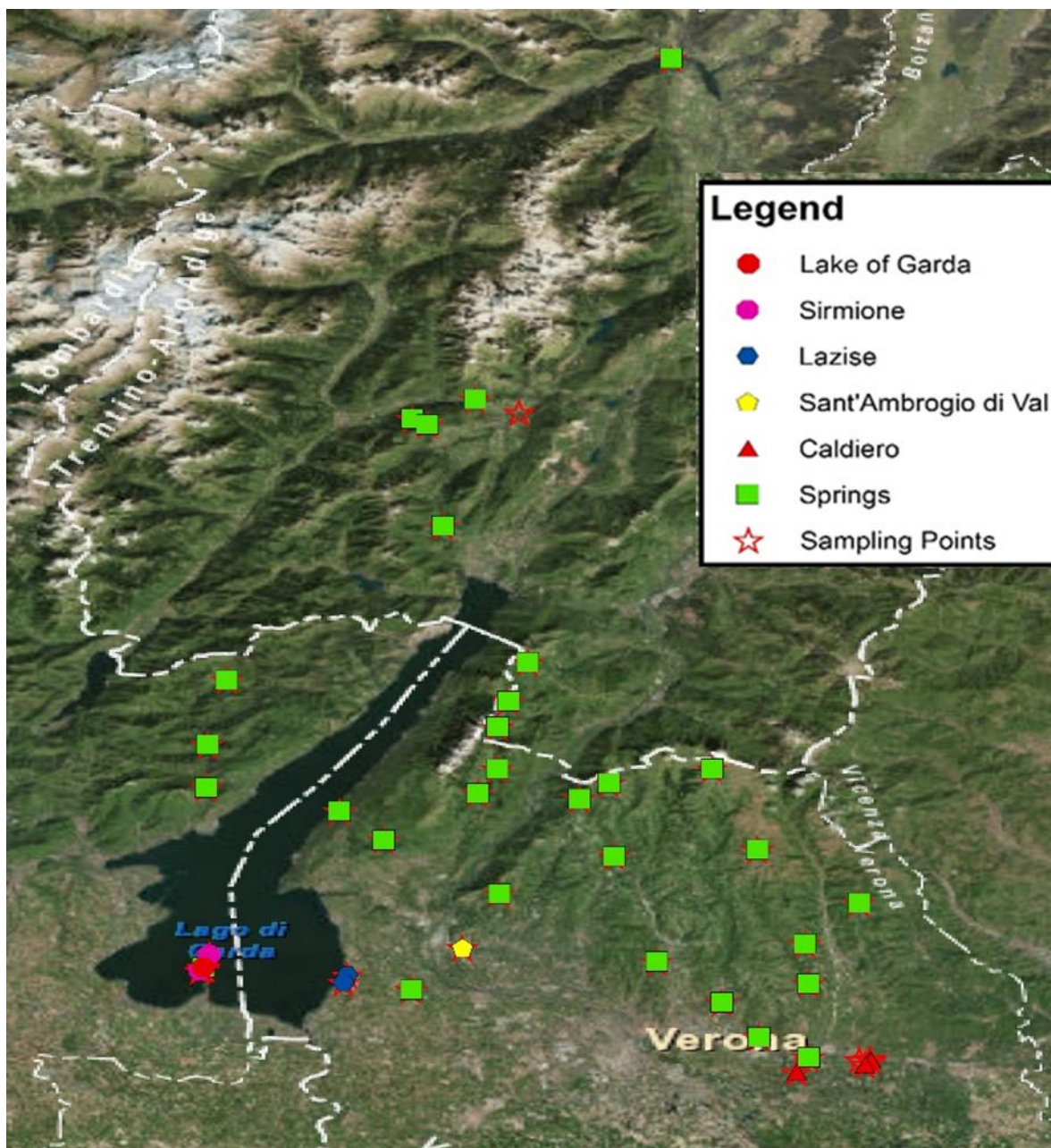
### *5.2 Water points network and field activities*

In order to face the above mentioned issues, the network of water points was defined including not only the waters of the thermal districts but also several cold water points located in the surroundings hilly and mountainous areas (Fig. 5.1).

The network is mainly comprised of wells and springs and of a few surface water points. Based on literature data, the choice of the points was done with respect to the aims of the study and taking into account their hydrodynamic representativeness, as follows:

- A) springs and wells that drain thermal groundwater to characterize the geothermal systems;
- B) cold springs with medium to high flowrate (from a few to tens of L/s), frequently of the karst type, as representative of the main shallow groundwater systems that could interact with the hydrothermal flow paths, especially where the latter raise;

- C) wells that could tap groundwater affected by mixing processes between cold and thermal components;
- D) water points within the Garda Lake to verify the possibility of interaction between this wide superficial water body and hydrothermal systems, with specific reference to the Sirmione system;
- E) low flowrate cold springs, which drain local groundwater systems that are widespread on the hills and mountains surrounding the thermal districts and, overall, on a wide range of altitude. These points were studied in order to achieve information both on water isotopes signature of the rainfall that infiltrate at different altitudes and on hydro-chemical features linked to specific lithologies. They constitute an important base of work that drive the interpretation of the data achieved for the other type of water points (A, B, C and D). Below photo 5.1.



As a whole, the sampling activities were carried out on 78 water points, which are distributed over an area of about 3000 km<sup>2</sup>, within the Provinces of Verona, Brescia and Trento.

In order to investigate on their seasonal behavior, most of the water points were twice sampled (in two different period), thus collecting a total of 121 samples.

The sampling activity provided the collection of various aliquots of waters for each point, accordingly the kind of analyses to be performed in laboratories:

- N°1 polyethylene (PE) bottle (125 mL) of no- treated water, for anions analyses;
- N°2 PE bottle (50mL) of no-treated water for the isotopic analyses of water stable isotopes and Sr;
- N°1 PE bottle (50mL) of filtered (0.45 µm) and acidified (HNO<sub>3</sub> 1:1) water for major cations and metals analyses;
- N°1 PE bottle (500 mL) of no-treated water for tritium analysis.

Before collecting samples, measurements of temperature, electrical conductivity (EC), pH, dissolved oxygen, Eh, flow rate, together with geographical coordinates and altitude were performed in each sampling site, by using portable instruments. Also, total alkalinity was on field determined by means of acidimetric titration, using HCl (0.1N) as a titrant and methyl-orange as pH indicator.

The data collected during the field activities are reported in appendix B. In figure the thermal points of every sampling locality. The temperature of samples must be >20°C.

### *5.3 Laboratory analyses and results*

Classical qualitative inorganic analysis is a method of analytical chemistry which seeks to find elemental composition of inorganic compounds. It is mainly focused on detecting ions in an aqueous solution, so that materials in other forms may need to be brought into this state before using standard methods. The solution is then treated with various reagents to test for reactions characteristic of certain ions, which may cause colour change, solid forming and other visible changes.

Modern techniques such as atomic absorption spectroscopy and ICP-MS are able to quickly detect the presence and concentrations of elements with a little sample of water.

Inductively coupled plasma optical emission spectrometry (ICP-OES) in figure, is an analytical technique used for the detection of elements in IGG-CNR of Pisa. It is a type of emission spectroscopy that uses the inductively coupled plasma to produce excited atoms and ions that emit electromagnetic radiation at wavelengths characteristic of a particular element. It is a flame technique with a flame temperature in a range from 6000 to 10000 K. It is also a solution technique standard silicate dissolution methods are employed. The intensity of this emission is indicative of the concentration of the element within the sample.

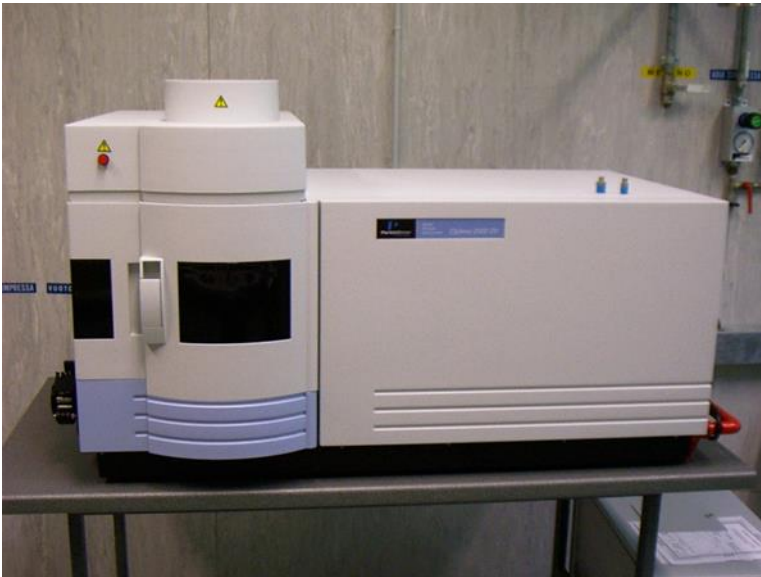


Figure 5.3.1 - ICP della Perkin Elmer mod.Optima 2000 DV

ICP-OES Laboratory of IGG-CNR Pisa has an Instrumental equipment Spectrophotometer ICP-OES JY38PLUS of JOBIN-Yvon. Laboratory is dedicated to the measurement of major, minor and trace solutions obtained by the dissolution of minerals, rocks, soils and groundwater samples (ICP-OES: Na, K, Ca, Mg, Ba, Rb, Li, Fe, Mn, Cu, Pb, Zn, Al, As, Hg, Sb, Be, Bi, B, Cd, Cr, Co, Mo, Ni, Sr e V).

With the equipment (monochromatic) present in the laboratory we cannot perform the determination of the elements belonging to the first group of the periodic table.

Laboratory AAS has a Spectrophotometer AAS 5000 Perkin Elmer, sampling Flame.

The Atomic Absorption Spectrometry is devoted mainly to the determination of the elements belonging to the first group of the periodic table and most of the major and

minor elements contained in the solution obtained from the dissolution of minerals, soils, rocks and groundwater samples.

The isotopic parameters taken into account in the following presented cases are the abundance ratios of the water stable isotopes ( $^{18}\text{O} / ^{16}\text{O}$ ,  $^2\text{H} / ^1\text{H}$ ),  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{34}\text{S}/^{32}\text{S}$ . The values are expressed as  $\delta\text{‰}$  compared to a standard (Fritz and Fontes, 1980), corresponding to the V-SMOW, for the first two ratios, and to Canyon Diablo Chondrite in the case of Sr and S (Hoefs, 2013). Waters sampling were carried out using bottles with double cap, the analyses were performed by mass spectrometry,



Figure 5.3.2 – Mass spectrometry of the Europa Scientific values (in the range, 2,5-2,7A) were reached at a slower rate (0,2mA/s)(Cavazzini, 2005).

in part at the isotopic-chemical laboratory of the Institute of Geosciences and Earth Resources, IGG-CNR (Pisa and Padua, Italy) and in part at Canada. In IGG-CNR of Padua I followed the long and complex procedure of the samples preparation of water for identification of Sr isotopes by Mass spectrometry. At the end, after the chromatography, the W single filaments (99,95% W; thickness, 0,001 in.; width, 0,020 in.) were degassed in a VG degassing unit under a pressure  $<2.0 \times 10^{-5}$  mbar according to the following procedure: 10 min at 2,2 A and 30 min at 3,3 A. A VG Micromass 54E single-collector mass spectrometer was used. Electromagnetic parameters and other approximate working conditions were: accelerating potential, 8 kV; approximate magnet current, 3,2 A; vacuum in the flight tube better than  $3 \times 10^{-8}$  mbar. The data acquisition program was by Ludwig 1993. Filament current was increased to 2.0 A at rate of 1mA/s. Thereafter, operating current

The  $\delta^{18}\text{O}$  value of water was determined through analysis of gaseous  $\text{CO}_2$ , previously equilibrated with water at  $25^\circ\text{C}$  (Epstein and Mayeda, 1953). The  $\delta^2\text{H}$  value of water was determined through analysis of gaseous  $\text{H}_2$  generated by the reaction at  $460^\circ\text{C}$  with Mg.

The analysis of geochemical data is fundamental for a correlation between thermal waters of Verona and Brescia and cold waters of Lessini Mountains and Alpine arc.

The chemist of water is given by equilibrium between rocks and fluids that leaching the rocks.

The reactions, which occur between fluids and minerals, have specific values of temperatures, pressure, and salinity that depend by crossing rocks.

These reactions produce secondary minerals that are stable in the conditions of formation.

In thermal water the concentration of solutes changes depending on heat source, type of crossing rock, permeability, age of geothermic reservoir, and origin of fluids.

In this thesis the ionic kinds of geothermal interest was analysed like:

- Ions with negative charge (anions)  $\text{Cl}^-$ ,  $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{F}^-$ ,  $\text{Br}^-$ ,  $\text{I}^-$
- Ions with positive charge (cations)  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Li}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Mn}^{2+}$
- Neutral ions:  $\text{SiO}_2$ ,  $\text{NH}_3$

According to Barbier, 2002 we can divide waters of studied area in three groups:

1. Sulphate waters. They are also known as 'acid-sulphate waters' and are invariably superficial waters formed by the condensation of geothermal gases into near-surface, oxygenated groundwater. Such fluids are highly corrosive to well casing and surface pipelines.
2. Bicarbonate waters. These waters, which include those termed  $\text{CO}_2$ -rich fluids and neutral bicarbonate-sulphate waters, are the product of steam and gas condensation into poorly-oxygenated sub-surface groundwater. They are highly corrosive on well casings.
3. Sulphate-chloride waters. These waters can form by several processes, of which the most common is the mixing of chloride and sulphate waters at variable depths.

Although the proportion of gas within the steam discharge is small, the concentration of the gases together with the gas/steam and steam/water ratios can yield important information on the subsurface conditions and on the behaviour of a field during exploitation.

As with the water-soluble constituents, geothermal gases can be conveniently divided into two groups (Barbier, 2002):

1. reactive gases,  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{NH}_3$ ,  $\text{N}_2$ ,  $\text{H}_2$ , and  $\text{CH}_4$ , which take part in the chemical equilibria and provide information on the sub-surface conditions such as temperature;
2. inert gases, noble gases, hydrocarbons other than methane, which act in an analogous manner to chloride in that they do not take part in chemical reactions.

Considering reactive and inert gases these more important for us are:

- Carbon dioxide,  $\text{CO}_2$ , is the most abundant gas in geothermal systems, often representing over 85% by both volume and weight of the total gas content of a discharge.
- Hydrogen sulphide,  $\text{H}_2\text{S}$ , gas is very common in geothermal fluids and may be produced by alteration of the reservoir rocks or from a magmatic source.
- Ammonia,  $\text{NH}_3$ , is the most soluble of the geothermal gases. High concentrations of ammonia can result from the alteration of organic matter in sedimentary rocks at depth or in near-surface environment.  $\text{NH}_3$  is carried in steam as a gas, but is highly soluble in water at lower temperature.
- Hydrogen,  $\text{H}$ , highly reactive gas, is readily removed on reaction with wall rocks.
- Nitrogen,  $\text{N}_2$ , being the principal atmospheric gas, most nitrogen in geothermal fluids is derived from that dissolved in the meteoric recharge waters, although it can also be of magmatic origin. Nitrogen tends to assume greater proportions in low temperature systems where it can be the major gaseous component.
- Oxygen,  $\text{O}_2$ , its presence in a gas sample often indicates contamination either by soil air or during the sample procedure, in fact oxygen contamination in uncontaminated samples is near or below the detection limit.
- Tritium,  $^3\text{H}$ , is the radioactive isotope of hydrogen, and deep geothermal fluids with long residence times commonly contain little tritium compared with modern surface waters. The tritium content of steam can therefore be used to differentiate between deep and shallow sources of the steam, to recognise mixing between steam from both deep and shallow sources, and to estimate the residence time of water or steam underground. Tritium is created in the atmosphere by the interaction of nitrogen with neutrons produced by cosmic radiation, and is transported into groundwater by meteoric water. The tritium concentration levels in rains rose after a series of thermonuclear detonation tests in the 1950s and reached the peak concentrations two orders of magnitude above the natural level. The tritium concentration in natural waters, or in the steam condensate, is expressed by tritium units (T.U.), 1 T.U. corresponds to a concentration of 1 tritium atom per 10<sup>18</sup> hydrogen atoms. The relatively short half-life (12.43 yr.) makes this isotope a valuable tracer of water movements (Barbier, 2002).

Analysing the tritium content in a groundwater the following cases can occur:

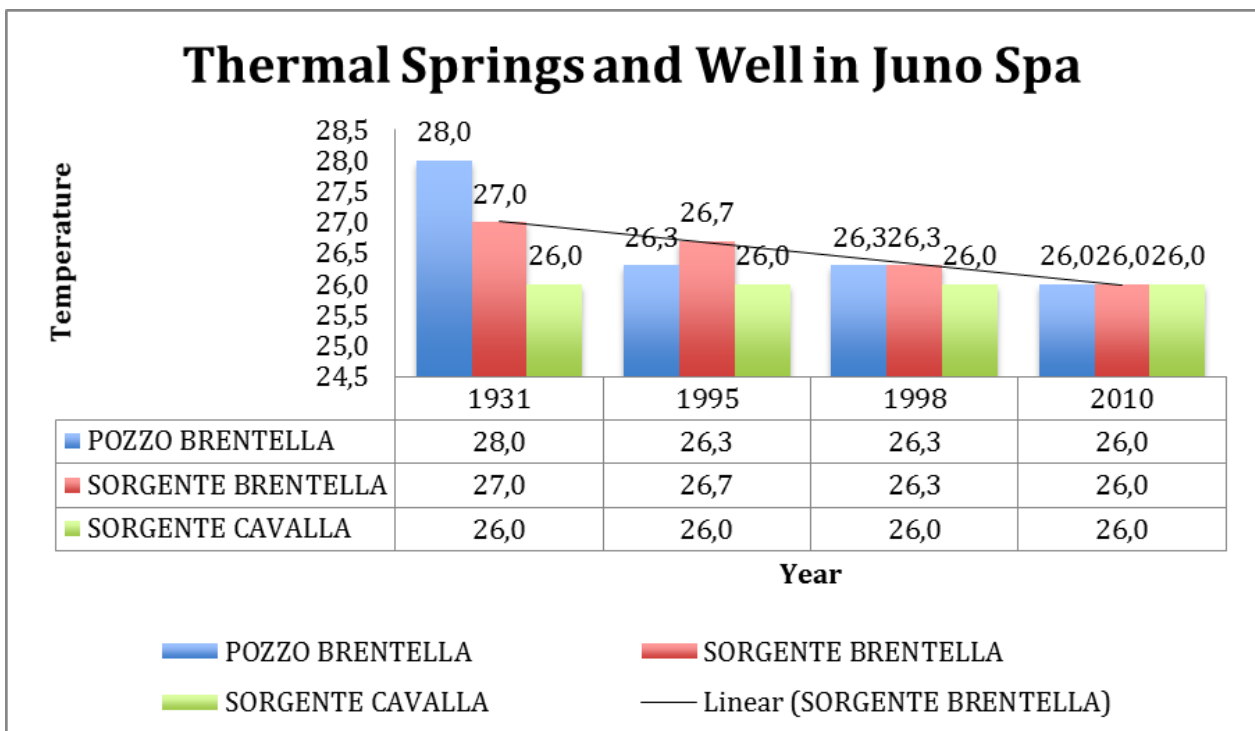
1. The water is tritium-free. This means that in the aquifer more than 40 years are required for the water to reach the sampling point from the recharge area.
2. The tritium content is appreciable and variable with time. This means that an appreciable amount of water younger than 40 years is present and the variations imply a short circulation time of the order of a few years. Another possibility is that water from two different sources is present: a mixing of an old tritium-free water and a young water containing tritium.
3. The tritium content is appreciable and constant in time. This means that the young water is well mixed in the aquifer with old water and the size of the reservoir masks any fluctuations in recharge.

### 5.3.1 Water Chemistry

In the study of a thermal aquifer it's better to consider, in each area studied, both the thermal water that cold water.

The water is said "thermal" when its temperature is higher, at least, five degrees than to the average annual temperature of the studied area. In my thesis the thermal waters are a temperature of about 20°C, because the average annual outdoor temperature is round 15°C.

As regards the aquifers places in depth and contained in rock or in flood "porous", higher values of 12/14 °C denote conditions of thermal anomaly.



These values are within a range between 20 to 31 °C for area of Caldiero, Belfiore, San Bonifacio (eastern plain in figure) and between 33/52 °C for area of Pescantina, Sant'Ambrogio di

Valpolicella, Piovezzano (northern plain) and between 22/24 °C for Lazise, Peschiera, Castelnuovo.

According to the classification of Moureu (1910) we consider cold water below 20 °C, while water with higher temperature than 20°C we can call thermal water with the difference shows in table.

Temperature °C	<20	20-35	35-50	>50
<b>Typology</b>	Cold	Ipo-thermal	Meso-thermal	Iper-thermal

The thermal events studied are given by unusual heat flow with deep underground water.

The thermal water, like all other waters, hold salts in solution dissociated in ions (cations and anions).

The total salinity and dominant characteristics chemical depend on the temperature in hydrogeological basin, on the geological environment.

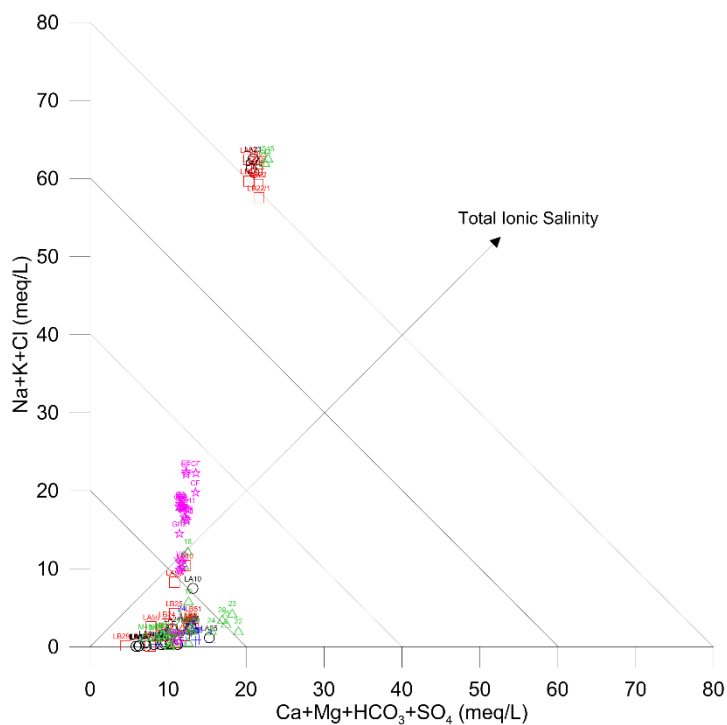


Fig. 5.3.1.1 Total Ionic Salinity values.

In table division in according to electrical conductivity.

Type of water	oligomineral	mediomineral	mineral
<b>Residuo Fisso in mg/l a 180° C</b>	<b>&lt; 200</b>	<b>200-1000</b>	<b>&gt; 1000</b>
<b>Electrical conductivity µS/cm a 20° C</b>	<b>&lt; 260</b>	<b>260-1320</b>	<b>&gt;1320</b>

In graph the values of samples follow an exponential trend. We can see the Sirmione values clearly separated from the other samples. Also the values of Sant’Ambrogio of Valpolicella are well separated from the group of warm waters of Caldiero, Lazise and cold water.

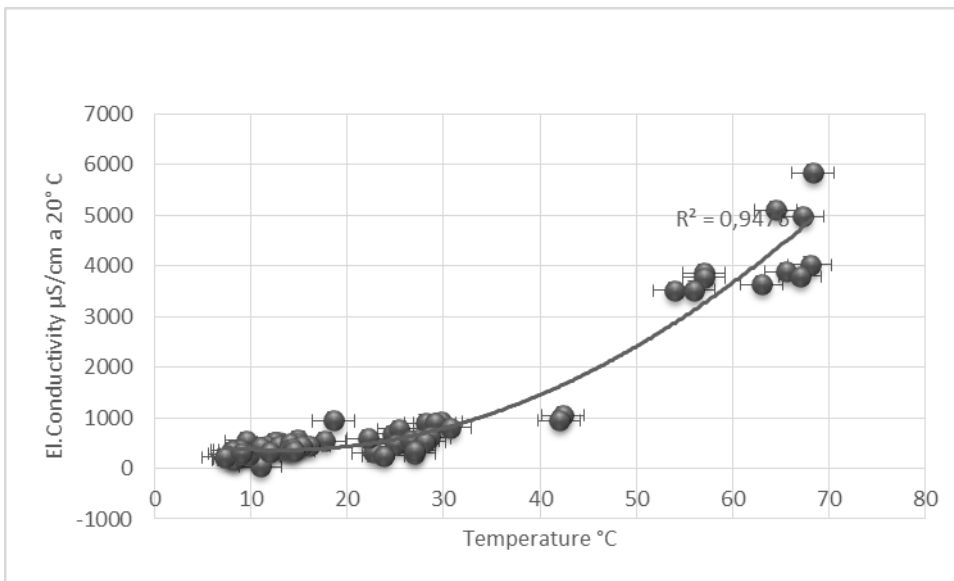


Fig. 5.3.1.2 Diagram T°C and Eh Conductivity at 20°C.

Hard of Water	Average Hard	Hard	Very Hard
Temperatura - ° C	27	46	52
Durezza - ° F	31,5	33,5	36,4

The pH values have a range between 6,5 and 7,96 making possible the existence of particular environmental conditions and hydrodynamic probably linked to plant contact with organic materials (peat).

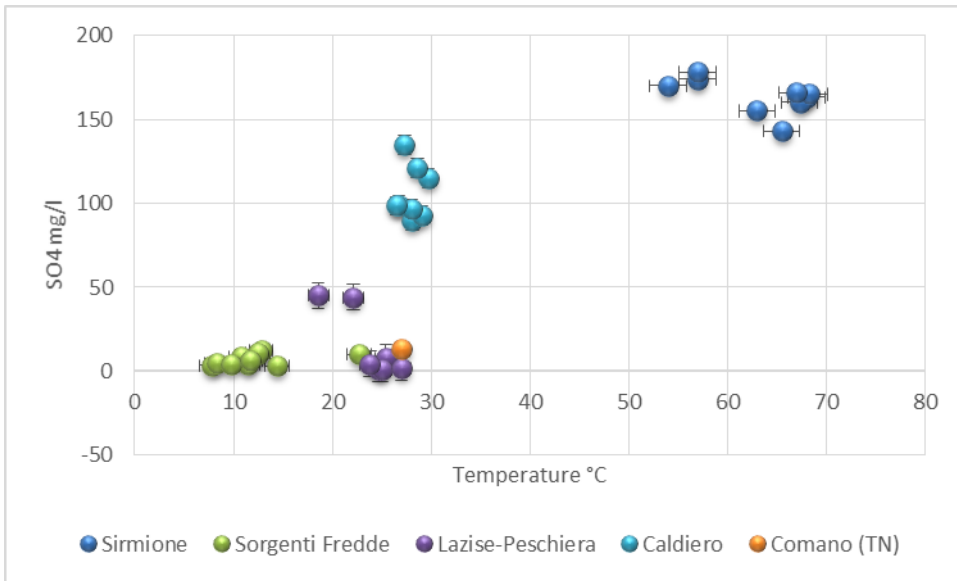


Fig. 5.3.1.3 Diagram T°C and SO4 values.

In general the thermal waters are all bicarbonate waters with varying amounts of sulfate ion and are to be connected to the circulation in soils essentially carbonate whose salinity is in direct proportion with the thermalism. In fact the waters with higher temperature have a salt content tends to be higher.

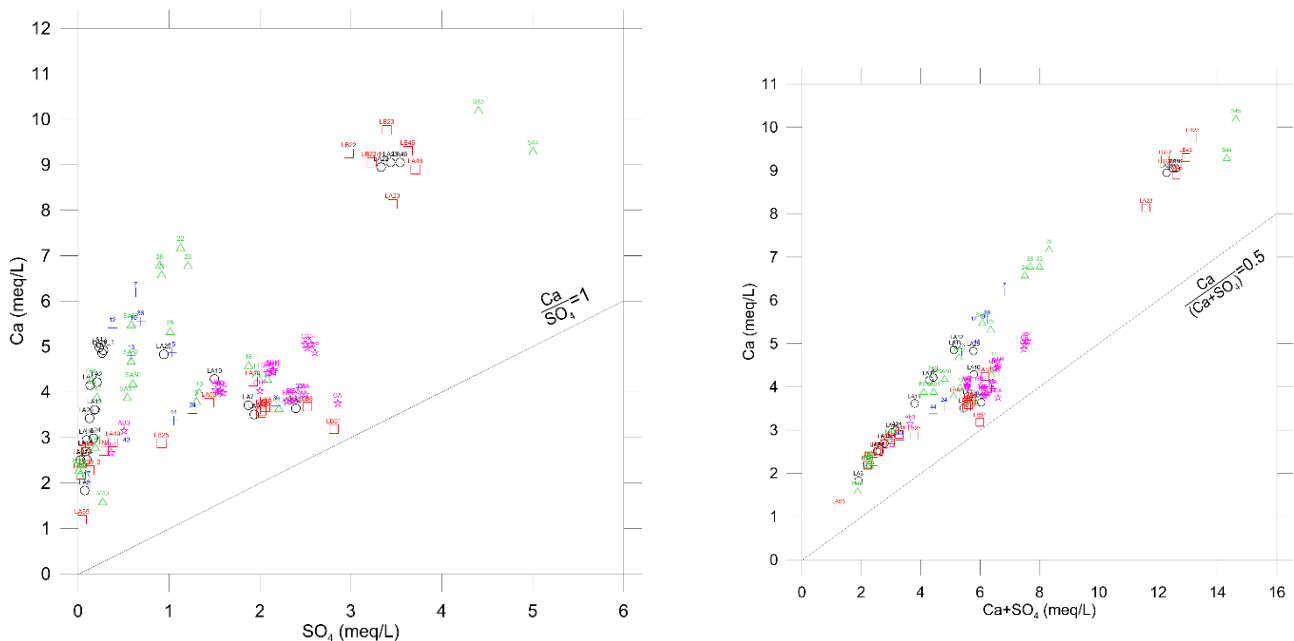


Fig. 5.3.1.4 and 5.3.1.5 SO4 and Ca, and Ca+SO4 and Ca. It is evident tha high content of Ca than SO4.

Sulfates, in particular, tend to be more abundant in quantity in the warm waters of the thermal zone of the northern plain in which it is plausible that the mineralization resulting from leaching of salt deposits in Triassic basement of regional substrate.

In graphic we must consider the values of sulphate of Caldiero that are very similar to values of NW thermal area (Sant'Ambrogio di Valpolicella, Pescantina). The reason would be:

- a path in the evaporate of Bellerophon Formation (Triassic age) located N respect to Lessini Mountain (Recoaro area);
- an interaction with the warm water coming from NW, along the Verona fault (SAV and Pescantina);
- both the warm waters, of Caldiero and SAV-Pescantina, pass through Bellerophon Fm of the Triassic basement (plausible assumption).

For the NW sector, in accordance with the tectonic and structural situation, there is the overlapping and duplication of stratigraphic series and consequently contact with gypsum-anhydrite minerals it is showed. The tectonic and structural situation is not so clear for the E warm sector, but the stratigraphic sequence it allows us to assume a north-deep infiltration.

The study of chloride help us to understand how is the circulation of warm water, giving us information on journey times.

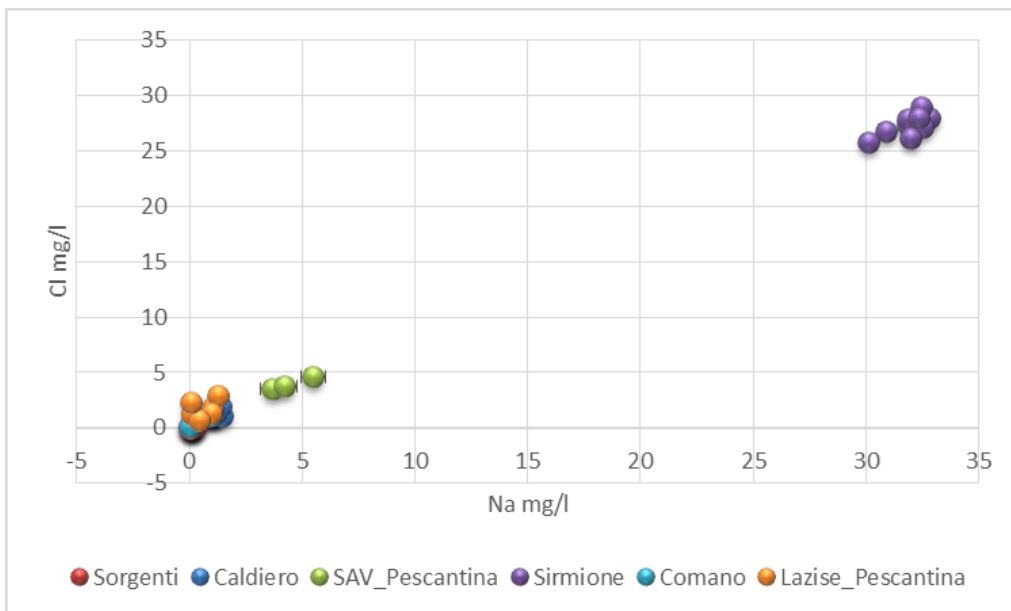
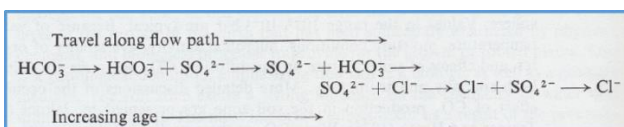


Fig. 5.3.1.6 In figure rate Na/Cl (only thermal water).



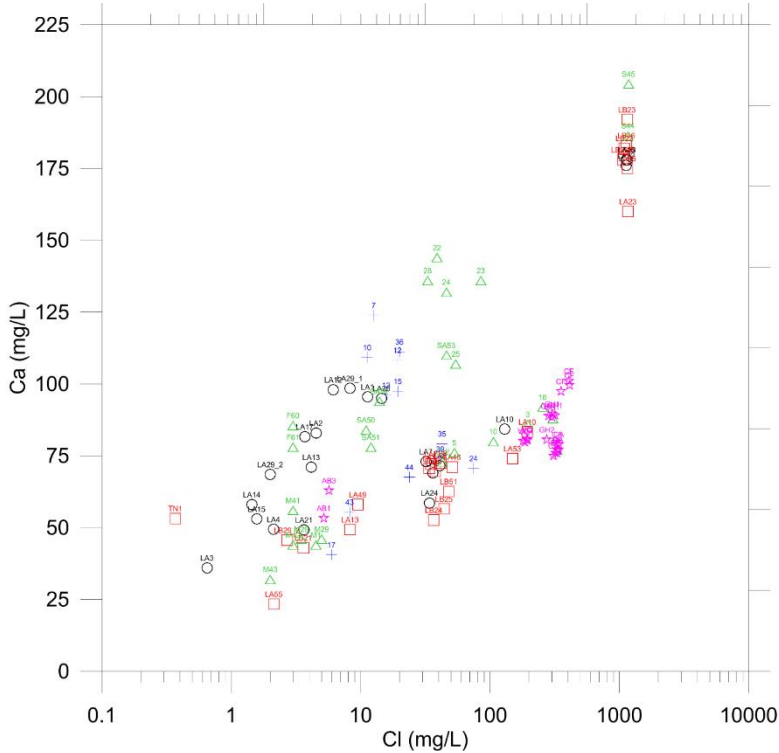
The chlorine ion is subjected to small transformations by ion exchange, for this reason it is regarded a good natural marker.

Its concentration increases if the warm water travels along flow path in the long time.

Temperatura - °C	27	46	52
Cloruri - mg/l	45	293	407

Acqua	dolce	deb. salmastra	deb. salmastra
-------	-------	----------------	----------------

In figure 5.3.1.6 the value of the chlorine of Sirmione thermal water is much higher than the values of other thermal areas.



These data are highly meaningful because suggest:

- ✓ a long and deep path for Sirmione thermal water;
- ✓ a deep path for SAV\_Pescantina thermal area;
- ✓ a strong mixing for Lazise\_Peschiera thermal area;
- ✓ a short path for Caldiero and, Comano, thermal area.

Also graphic Ca/Cl shows a different

Fig. 5.3.1.6 In figure rate Na/Cl (all values sampling in right image).

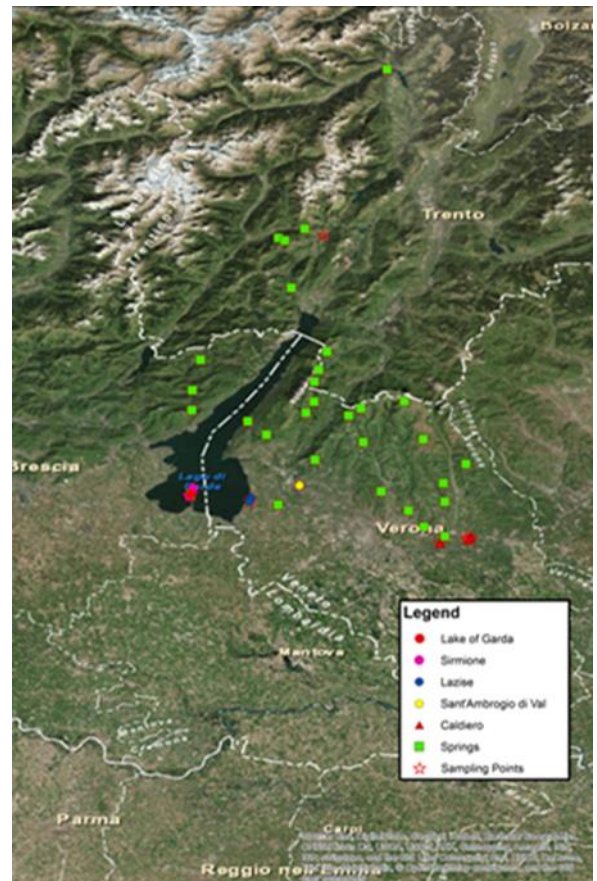
trend for Sirmione thermal area compared to other thermal area. The values of SAV and Pescantina prove a greater proximity to the values of Sirmione thermal water.

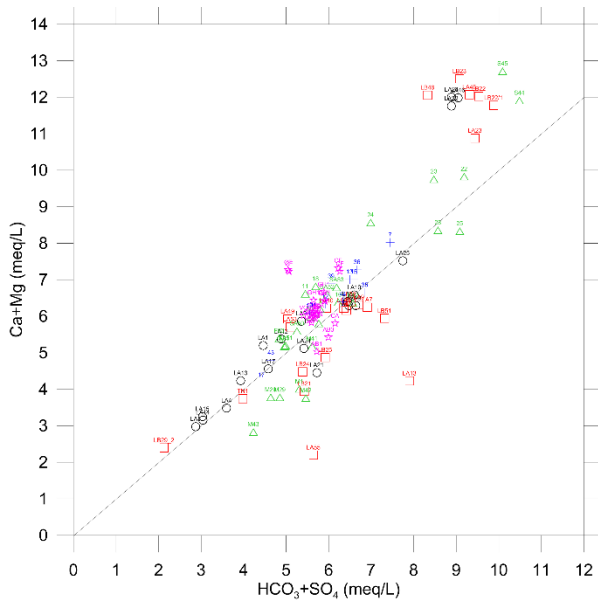
Therefore the values of cations and anions obtained have allowed us to do some interesting considerations. The main cations are represented by  $Ca^{2+}$ ,  $Mg^{2+}$ ,  $Na^+$ , and  $K^+$ ; main anions are represented by  $Cl^-$ ,  $SO_4^{2-}$ , e  $HCO_3^-$ .

Other important chemical species are:  $SiO_2$ ,  $Li^+$ ,  $Br^-$ , and  $NH_4^+$ . In the mesothermal events there are also some gases:  $CO_2$ ,  $H_2S$ ,  $N_2$ , etc.

The results of analysis, that now are shown, can be expressed as mg/l or meq/l.

If we consider only few springs and all thermal wells sampling we can already observe a marked difference





between Sirmione, western area of Verona and Caldiero. In a triangular diagram with alkali-ions we can note a remarkable difference in alkali component between Sirmione and all others samples.

Fig. 5.3.1.7 In figure rate between anions and cations.

All archive data and all sampling data are shown in Piper diagram, we can make further considerations with a total of 153 samples.

In the tables attached in the appendix there are five thermal centres, some private wells and a lot of cold springs. The old data were recovered by Regione Veneto, Dal Degan and Gambillara thesis. While the data from the thesis regard a lot of thermal and cold wells in the Verona Province, the data of Regione Veneto are only representative of some thermal wells in spas of western Verona.

In Piper diagram are showed all values of studied area with a “growth” trend from Caldiero thermal area to Sirmione thermal area.







Summing we can divide the water according to the salt content.

Table with classification about salt content and temperature:

AREA STUDIED	CLASSIFICATION	TEMPERATURE
SAV e Pescantina	BICARBONATE CALCIUM-MAGNESIUM	33-44°C
Caldiero	BICARBONATE CALCIUM-ALCALINE	27-31°C
Lazise	CLORURATE CALCIUM-SULFATE	21-25°C
Sirmione	CHLORINATED SODIUM	67-69°C



### 5.3.2 Chemical geothermometry

The elements as Na, K, Mg, Ca and chemical compound  $\text{SiO}_2$  are used to infer about the physico-chemical processes during the ascent of water to surface and, also used in geothermometry applications.

Geothermometry applications are not simply inserting values into specific geothermometry equations. In fact interpretation of temperatures obtained from geothermometry equations requires a “sound” understanding of the chemical processes involved in geothermal systems. The main task is to verify or disprove the validity of assumptions made in using specific geothermometers in specific fields.

The Silica geothermometers is based on the experimentally determined temperature that dependent on variation of the solubility of silica in water. Silica can occur in various forms in geothermal fields (such as quartz, cristobalite, chalcedony, amorphous silica) different silica geothermometers have been developed by different geochemists.

In our research we used silica and alkali geothermometers but before we considered:

- ✓ temperature range in which the equations are valid effects of steam separation possible precipitation of silica before sample collection (during the travel of fluid to surface, due to silica oversaturation)
- ✓ after sample collection (due to improper preservation of sample) effects of pH on solubility of silica
- ✓ possible mixing of hot water with cold water.

Silica geothermometers are usually used to temperature range up  $250^\circ\text{C}$  because, above  $250^\circ\text{C}$ , the equations depart drastically from the experimentally determined solubility curves.

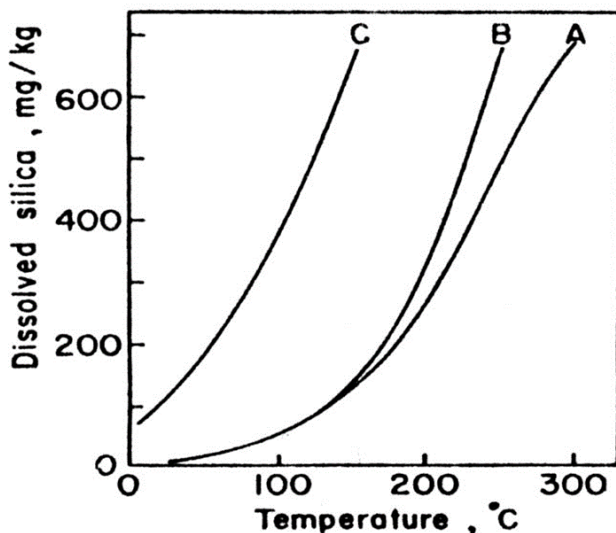
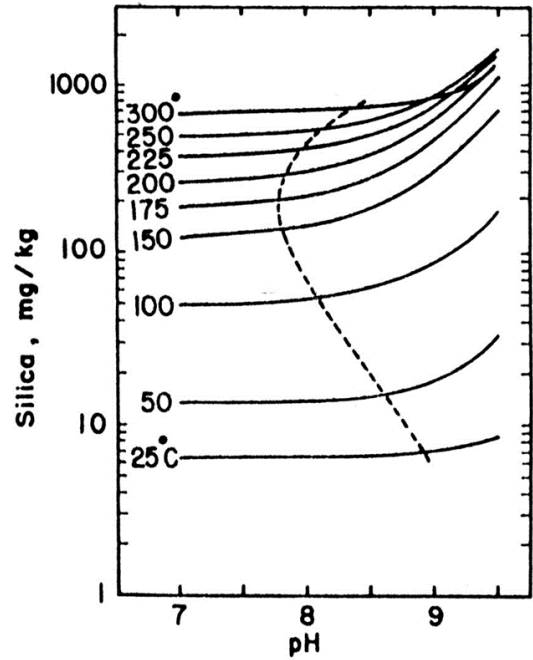


Fig.5.3.2.1. Solubility of quartz (curve A) and amorphous silica (curve C) as a function of temperature at the vapour pressure of the solution. Curve B shows the amount of silica that would be in solution after an initially quartz-saturated solution cooled adiabatically to  $100^\circ\text{C}$  without any precipitation of silica (from Fournier and Rowe, 1966, and Truesdell and Fournier, 1976).

Fig. 5.3.2.2. Calculated effect of pH upon the solubility of quartz at various temperatures from 25°C to 300°C, using experimental data of Seward (1974). The dashed curve shows the pH required at various temperatures to achieve a 10% increase in quartz solubility compared to the solubility at pH=7.0 (from Fournier, 1981).



Therefore we considered the chemical physical processes to understand what kind of geothermometer we had to use.

In fact with steam separation we have a overestimated reservoir temperature; with silica precipitation a underestimated reservoir temperature; an increase of pH overestimated and with a mixing with cold water (Caldiero thermal area) underestimated.

The trend lines for both geothermometers illustrate an exponential increase, which is expected (Arnorsson, 2000) of such geothermometers and could be used to estimate temperature conditions based on silica concentration in a given solution.

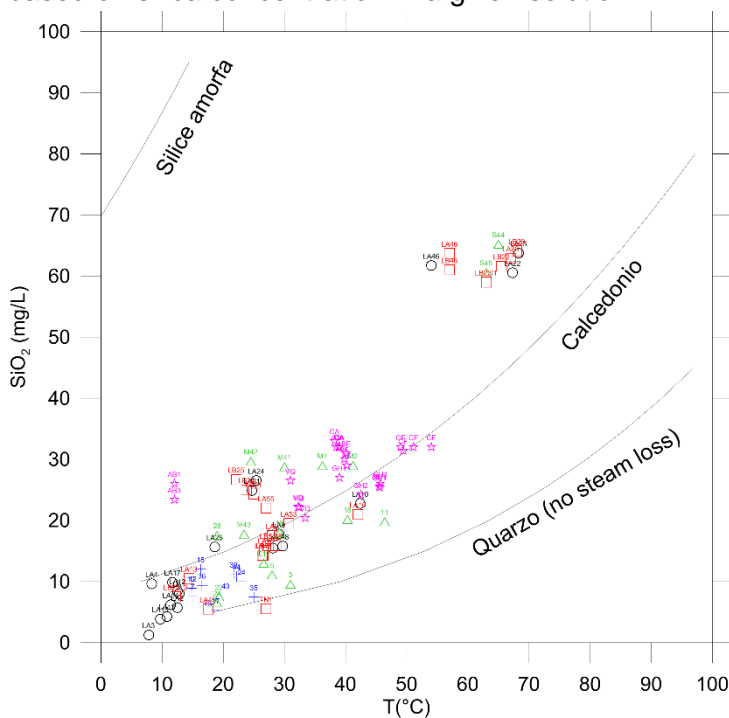
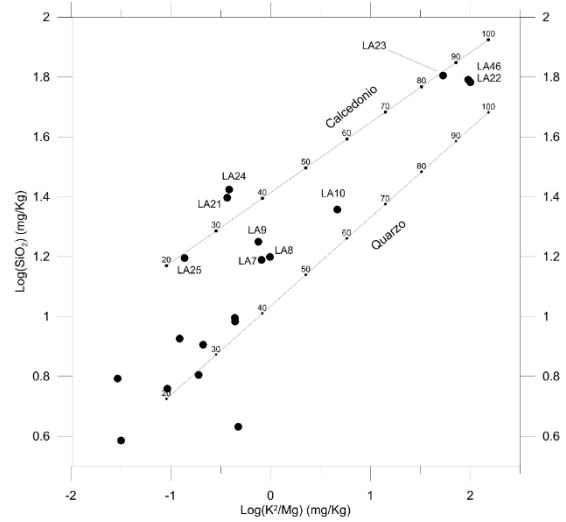
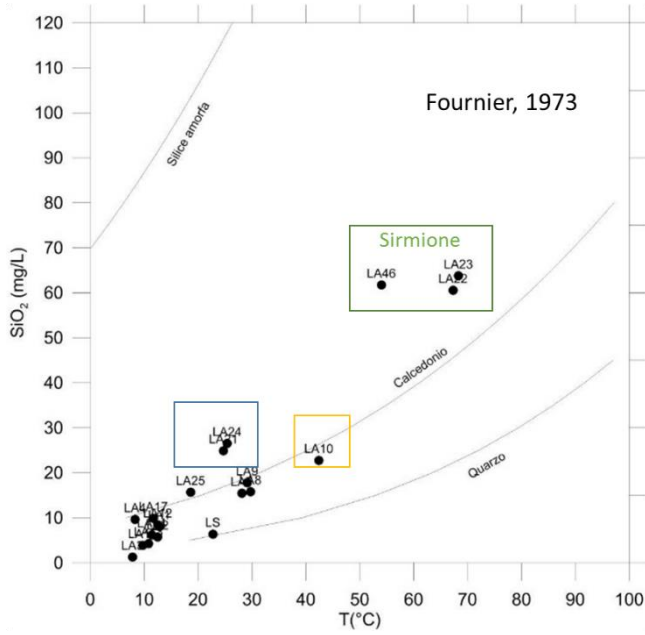
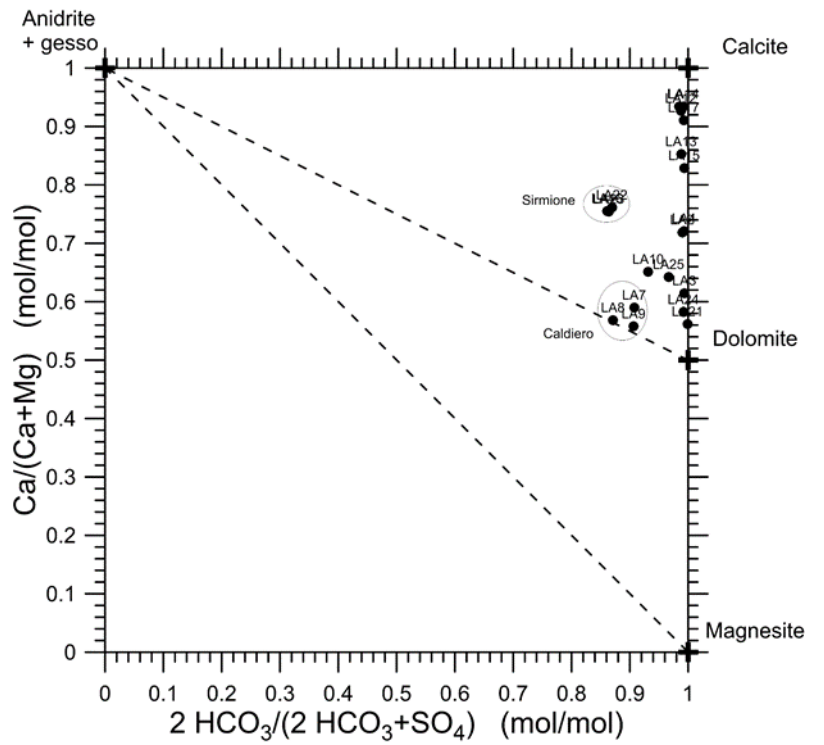


Fig.5.3.2.3 The silica data of all samples and of archive ( Fournier, 1973).

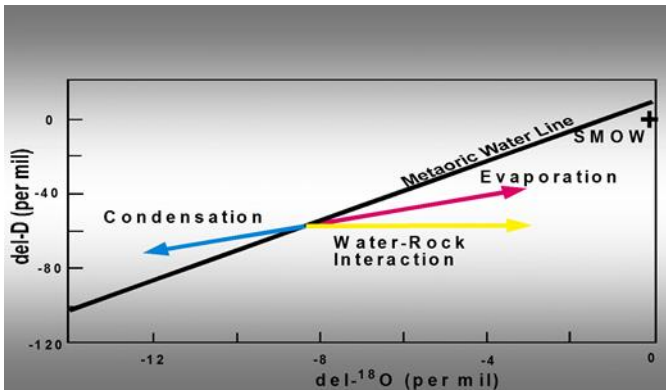


The silica geothermometer shows a reservoir range of temperature of 70-80°C, while the other thermal water seem not in equilibrate state.

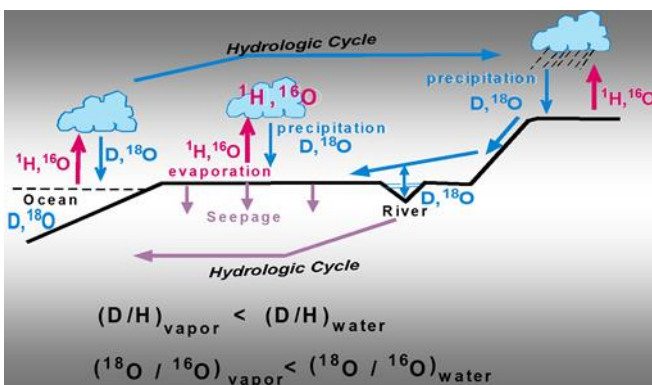


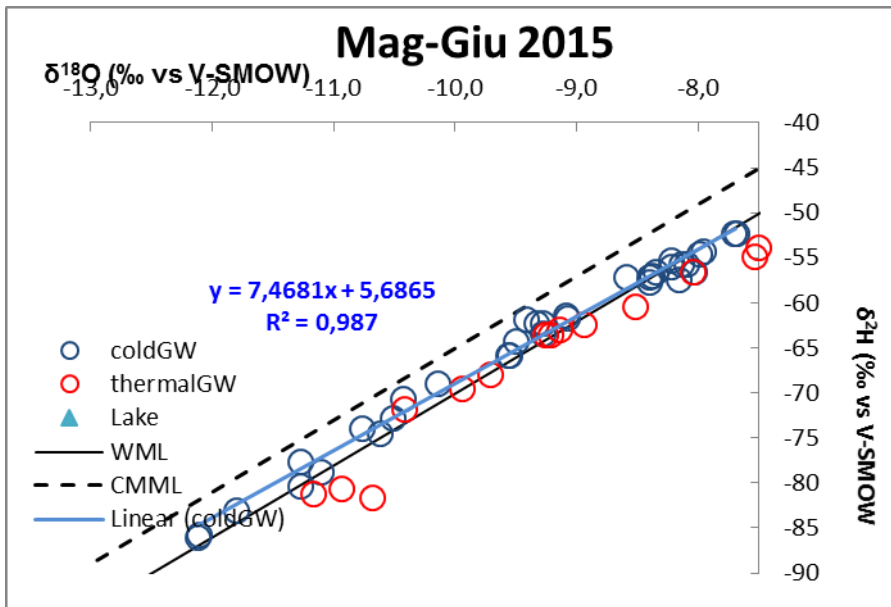
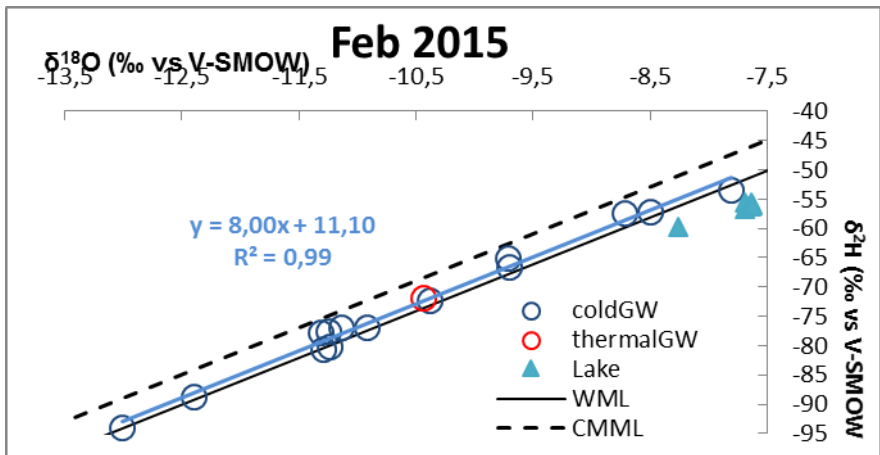
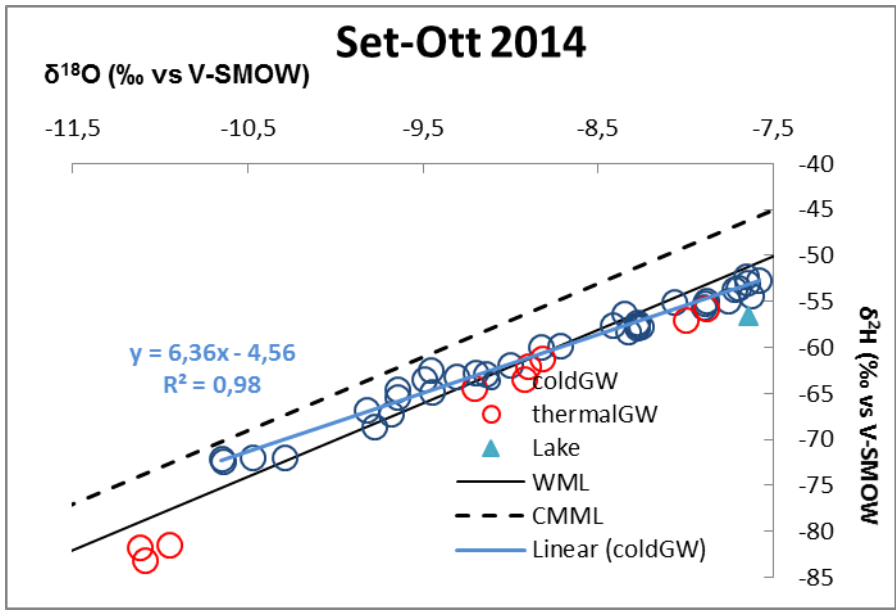
### 5.3.3 D and <sup>18</sup>O Isotopes

The origin of the thermal fluids is to be put in relation to a large hydrothermal circuit extended to regional level, developed within the mountainous and hilly reliefs of dominant limestone composition. In this manner, the rainwater falls in alpine and prealpine are absorbed and channeled deep. In order to get an indication on the share of infiltrations of these rainwater it has been referenced to the concentration of the <sup>18</sup>O oxygen isotope in thermal waters.



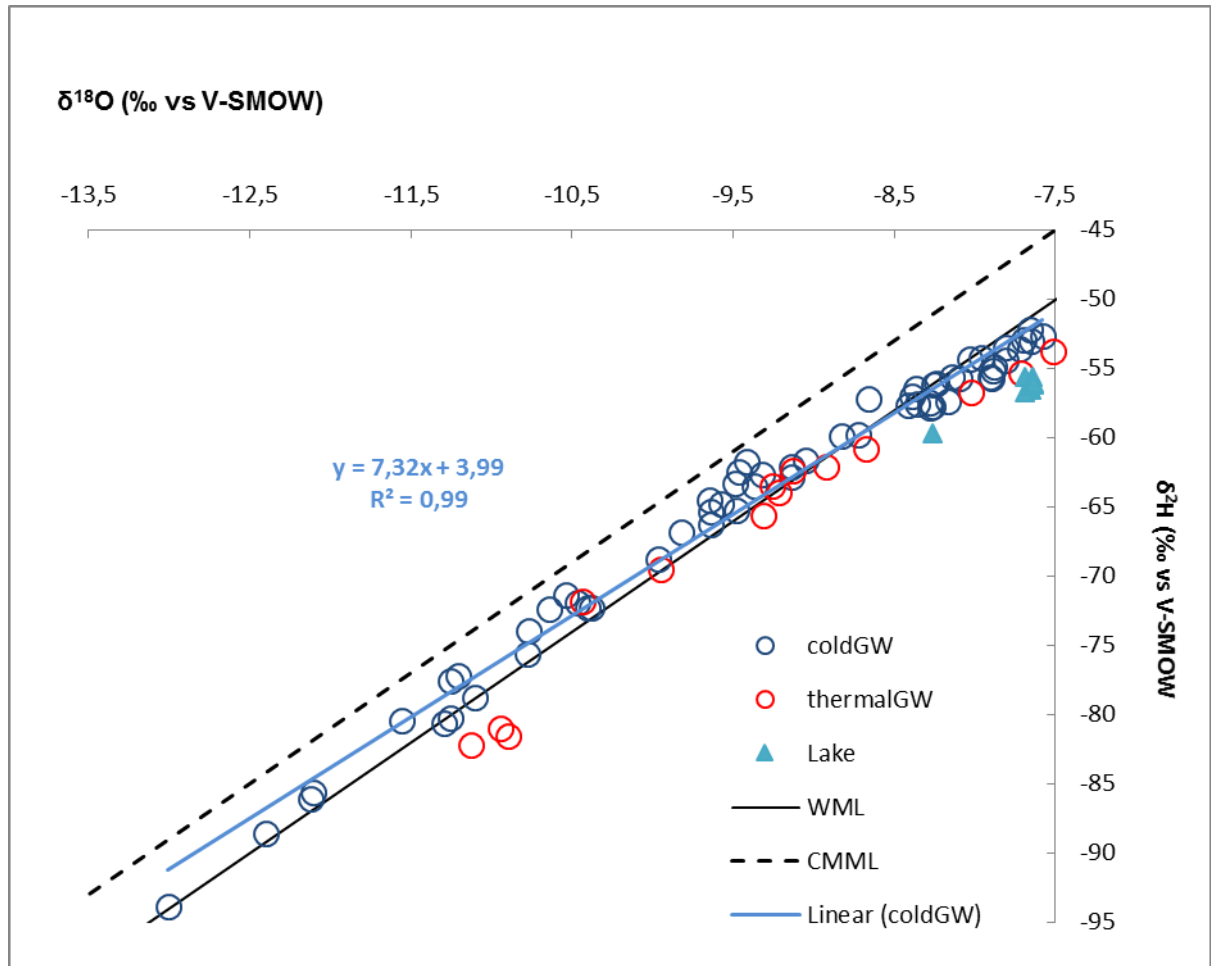
The few available historical data have been published by Sighinolfi et al., 1982 where considered different areas of the Po Plain including Veronese area. The historical values of <sup>18</sup>O and these of the sampling fields show that it is more negative when the temperature is higher ( $\delta^{18}\text{O} = -8,2$  a  $-9,1\text{‰}$ ). Exploring the geological-tectonic situation of veronese-trentino zone and the data of <sup>18</sup>O, the recharge area is situated at an average altitude of 1500-1700 meters for the Lessini Mountains, in figure, while 3000 meters for Gruppo del Brenta (hypothetic recharge area of Sirmione thermal water).





The higher values of dD and d18O aquifers recharged by precipitation from lower altitudes.

The lower values of dD and d18O aquifers recharged by precipitation from high altitudes.



The correlation D and <sup>18</sup>O indicates a recharge area which corresponds to the samples of water taken in high lessinia, while the recharge area of Sirmione thermal water is much further to the

Sample	Trizio (U.T.)	errore +/- (U.T.)
TN1	2,7	0,5
LA22	0,0	0,4
LA46	0,0	0,4
LA9	0,4	0,5
LA10	2,8	0,6
LA13	3,6	0,7
LA24	0,3	0,4
LA19	4,4	0,7

N than it was assumed until now.

The Trizio activity is established for use in dating of waters to indicate the depth of mixing processes. The age calculated by Trizio activity refers to average age of residence in that aquifer.

Now despite not having specific dating to the thermal district of the Veronese plain, we can reasonably think that the W thermal area in Verona Province has a time of residence greater than the E thermal area. In fact the sample LA10 (SAV\_ Pescantina) shows a Trizio

value greater than LA9 (Caldiero).

#### 5.3.4 Sr and S Isotopes

The isotopes of Sr and S helped us to define the scheme of water circulation and recharge area. The Sr isotopes distinguish subduction related magmatic heat sources associated with marine sediments from fluids of non-magmatic origin.  $^{87}\text{Sr}/^{86}\text{Sr}$  has been used to indicate source rocks of geothermal fluids.

Six samples was analysed by Dr. Cavazzini of IGG-CNR of Padua.

The results shows an interaction evident with rocks of Tertiary. However, hypothesizing a relationship between the rocks in the studied area and the thermal waters we saw a similitude.

IP	$^{87}\text{Sr}/^{86}\text{Sr}$
LA7	0,707999
LA 9	0,708136
LA13	0,707835
LA 10	0,708506
LA 23	0,708614
LA 46	0,708641
<b><math>^{87}\text{Sr}/^{86}\text{Sr}</math> normalized to value of <math>^{86}\text{Sr}/^{88}\text{Sr}</math> di Nier (1938)</b>	

The values of thermal waters, except LA13 (cold water) are corresponding with values of dolomitized limestone (Cervato, 1992).

The ratio,  $^{34}\text{S}/^{32}\text{S}$ , is used in  $\text{SO}_4\text{-H}_2\text{S}$  geothermometry and to indicate sources of  $\text{SO}_4$  acidity commonly encountered in geothermal systems associated with volcanism as well as for environmental studies to identify the origin of local acid rain.  $\text{SO}_4$  also contains the isotope  $^{18}\text{O}$ , which can be applied to trace the processes undergone by the fluids (Annorson, 2000).

# Chapter 6

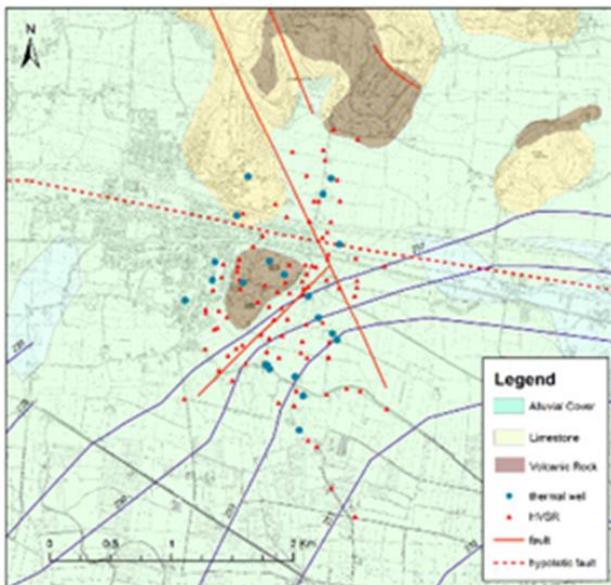
## *Detailed Studies*

### *6.1 Study of the Thermal basin of Caldiero area*

The Spa area is located in the high plains of Verona, between the pedealpine margin and the Adige River. High temperature aquifers are located in the loose sedimentary deposits of the Pleistocene and Holocene age. The sedimentary deposits are mainly gravels and sands, poorly differentiated, typical of fluvio-glacial and fluvial facies. This alluvial sedimentary material derived from the weathering of sedimentary and igneous alpine formations, and it also contains fragments of volcanic rocks of the Permian.

#### *Geological and tectonic setting of the studied area*

The lithostratigraphic succession of the Caldiero district includes sedimentary formations (Roghi and



Romano, 2008) ranging from the Upper Cretaceous ('Scaglia rossa') to Eocene (the limestone 'Calcari nummulitici') interspersed with different Paleogene volcanic rocks. During the Eocene the sedimentation of limestone, clayey limestone,

Fig.6.2.1.1 - Geological sketch map of the studied area with thermal wells and HVSR measurements positions. In evidence the basaltic hills of Caldiero, M.te Gazzo and M.te Rocca, and the main faults (Agostini et al., 2015).

marl and calcarenite was interrupted by the deposition of fine-grained laminated volcanic rocks (De Vecchi and al. 1977; Barbieri and al. 1991). In the Caldiero district there are volcanic rocks such as

breccias, tuffs and ialoclastiti, eocenico clayey limestone and marl, oligocenico sandstones, and, finally, paleo-soils and colluvial covers (Fig.6.2.1.1).

The outcrops of these rocks are much fractured mostly next to the tectonic structures. Local high permeability, due to the fracturing of the rocks, helps the infiltration of the rain that feeds small springs (Cavalla and Brentella springs).

Tectonics plays a key role in the thermal resources development of the area. Geo-stratigraphic and geophysical evidences indicate that the original arrangement of the rocks, which host the main aquifers, has been significantly modified by several tectonic events (Sighinolfi et al. 1982; Sorbini et al. 1984). The Southern area of the thermal basin shows, in fact, the presence of an evident depression, highlighted by recent remote sensing results, probably related to deep tectonic structures hidden by the fluvial sediments (see gravimetric studies ISPRA- Gravimetric Map of Italy 1:250.000, 2004).

The structural setting of the site is the result of crustal events that took place in the context of the Alpine orogeny. The Eastern sector was subjected to less deformation with respect to the Western part, which was interested from the main Alpine compressive phase (Caputo and al. 2010), and has a tabular structure slightly arched and dipping S-SW. The main structural elements are constituted by numerous dislocations, almost exclusively disjunctive.

The faults, in this area, can be grouped in two main orientations, respectively NW-SE and W-E. The first orientation can be related to extensional tectonics of the Paleogene (Accorsi and al. 1993; Zampieri, 2000), the second direction is linked to the structural system of the Schio-Vicenza fault (Cantelli and Castellarin 1994), activated during the most recent phases of the Alpine orogeny (Pola et al. 2014). The termination of the foothills to the South is probably related to an important fault. This fault, called variously in the literature as the Verona Fault (Panizza et al. 1981), Fault of S. Ambrogio Valpolicella (Cassinis et al. 1981), a town to the west of Verona, or fault of deformation (Zanferrari et al. 1982; Carton and Castaldini 1985), is buried for most of its path, thus making its nature and its extension uncertain due to the lack of direct evidence. According to Cassinis et al. (1981), the fault is subvertical-transcurrent with left kinematics and would extend from Verona to

Torri del Benaco, a town on the shore of Lake Garda. According to Panizza et al. (1981), Zanferrari et al. (1982) and Carton and Castaldini (1985), instead, the lineament of uncertain nature would probably cross the area in study studied area.

As can be noted in figure 6.2.1.2, obtained from LiDAR DTM (Light, Detection and Ranging; Digital Elevation Model) the main thermal areas are located at the SE margin of two small volcanic reliefs (Mt. Rocca and Mt. Gazzo, Fig.6.2.1.1) that represent the Southern fringe of the Lessini Hills (Fig.6.2.3). The spring area lays at the bottom of a terrace that separates the fans related to the Lessini rivers deposition activities from the Adige river fan. The Adige is one of the most important river of the North-East Italy which runs at the south of the studied area.

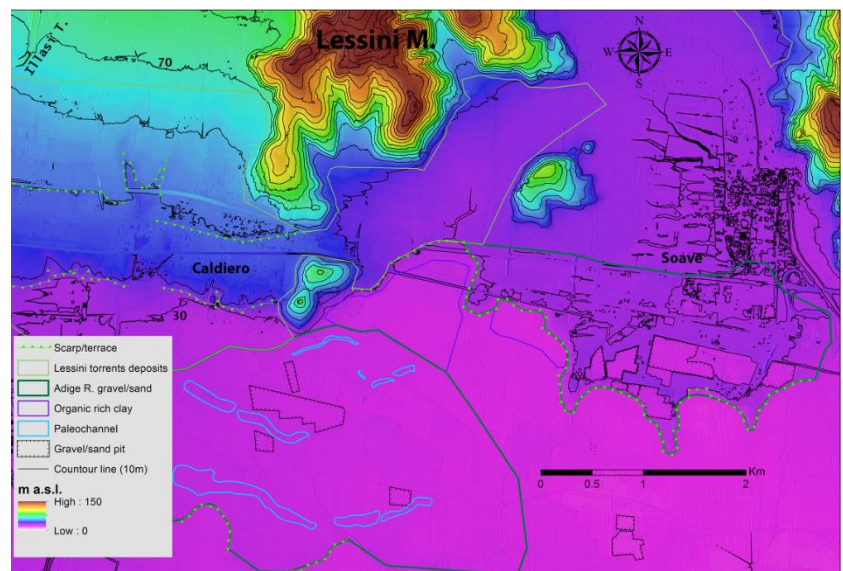


Fig. 6.2.1.2 - Geomorphological sketch map of the studied area obtained from LiDAR Images (Agostini et al., 2015).

The situation on the lithostratigraphic blanket containing alluvial aquifers studied is known through drilling wells. In fact, the subsoil of the high plains of Verona is formed from deposits in large prevalence gravelly-sandy, intercalated with thin and discontinuous layers of sediment of clay and silt. The coarse component is made up rounded elements, lithologically heterogeneous of fluvio-glacial origin.

They make up correspond to the aquifers found at variable depth, usually under pressure being delimited by waterproof material impervious materials. We can be expected rapid flow of water in the subsoil by lithological, morphological and hydrological characteristics of the aquifer recharge areas.

Sandy gravel deposits form the Adige fan and are well differentiated from the more fine sediments of Lessini creeks (silty clay with some stone blocks). The deposits in this area show some meandering paleohydrography if compared to the plain of the upper parts and are interrelated with silty sediments (Meneghel 1987).

The superficial granulometry of the area indicates that the Central and Eastern part of the thermal area, is constituted by an organic rich fine sediment (dark clay), well visible also in the orthophotos. This indicates swamp like deposits, which are probably related to the coming out of the “natural” thermal spring. On the Western sectors of the Adige River, sands stripes border with the colluvial deposits of the Mt. Rocca.

The reservoir of the thermal groundwater is mostly of carbonatic nature as the Euganean-Berico Hills ones (Gherardi et al., 2000; Sighinolfi et al., 1982). The groundwater of the main thermal spring has temperature of about 30°C; the thermal gradients are very different (see below Fig.6.2.1.3).

The local geothermal gradient, which could be defined as low, turns the Caldiero water district into a scarcely utilizable resource. A further and better knowledge of the thermal basin may allow increasing the potential of a geothermal resource exploitation in a sustainable way.

### Geophysical study

In these three years many geophysical investigations were performed to characterize the thermal basin with HVSR method and Reflection Seismology.

The area of Caldiero is focused mainly in the neighborhood of Caldiero, but also brings together the towns of Belfiore, Colognola ai Colli, Lavagno, S. Martino Buon Albergo, S. Bonifacio, Zevio, Ronco all'Adige and Arcole. These thermal wells have not been studied in detail due to time constraints.

After analyzing the geology of the area with a geological relief and controlled the stratigraphic wells present in the territory, a 103 HVSR single station measurements were collected. I use the HVSR technique (also known as Nakamura's technique; Nakamura 1989) because it consists in the passive

recording of natural microtremors (seismic noise) by the use of three component broad band receivers. The method aims to identify the subsoil resonance frequency  $F_0$ , assumed as the maximum peak of the ratio between the horizontal and vertical components of motion (Field and Jacob 1993). HVSR technique proved to be an efficient tool for estimating the fundamental frequency response  $F_0$  of soft deposits, e.g. bedrock and sediments (Field and Jacob 1995).

The measurements, after to be were calibrated on the stratigraphy of 21 of 125 wells tested, enable us to define the deep of bedrock and fractured rock. The final result is a bedrock map that it is possible to see in Appendices sector H Original Contributions. In fact, bedrock depth estimation, in previous studies, is in very good agreement with the HVSR results. In the right it can be seen as resonance frequency values decrease toward south direction as attended due to the deepening of the bedrock. The abrupt difference in resonance frequency behavior seems in good correlation with the fault system of the area (see Fig.6.2.1.2).

Further measurements of HVSR were performed to complete a survey of the detail using the statistical method (read Trevisani et al., 2016 to be published). This article present a rigorous integrated statistical approach to retrieve structural information from passive seismic surveys, highlighting advantages and limits of such geophysical prospection, applied statistical approach to an experimental dataset of more than 100 single station microtremor measurements collected in a small thermal basin in N-E Italy (the Caldiero Basin). The results show as critic data scrubbing, joined to rigorous statistical approach for data interpolation, are mandatory to assure meaningful structural interpretation from mictromeror HVSR survey.

In June 2015, thanks to the collaboration of OGS (Istituto Nazionale di Oceanografia e di Geofisica di Trieste) a new investigation was performed using seismic reflection. The method required a controlled seismic source of energy, in this case it's used a seismic vibrator, commonly known by the trademark name Vibroseis (see photo below).

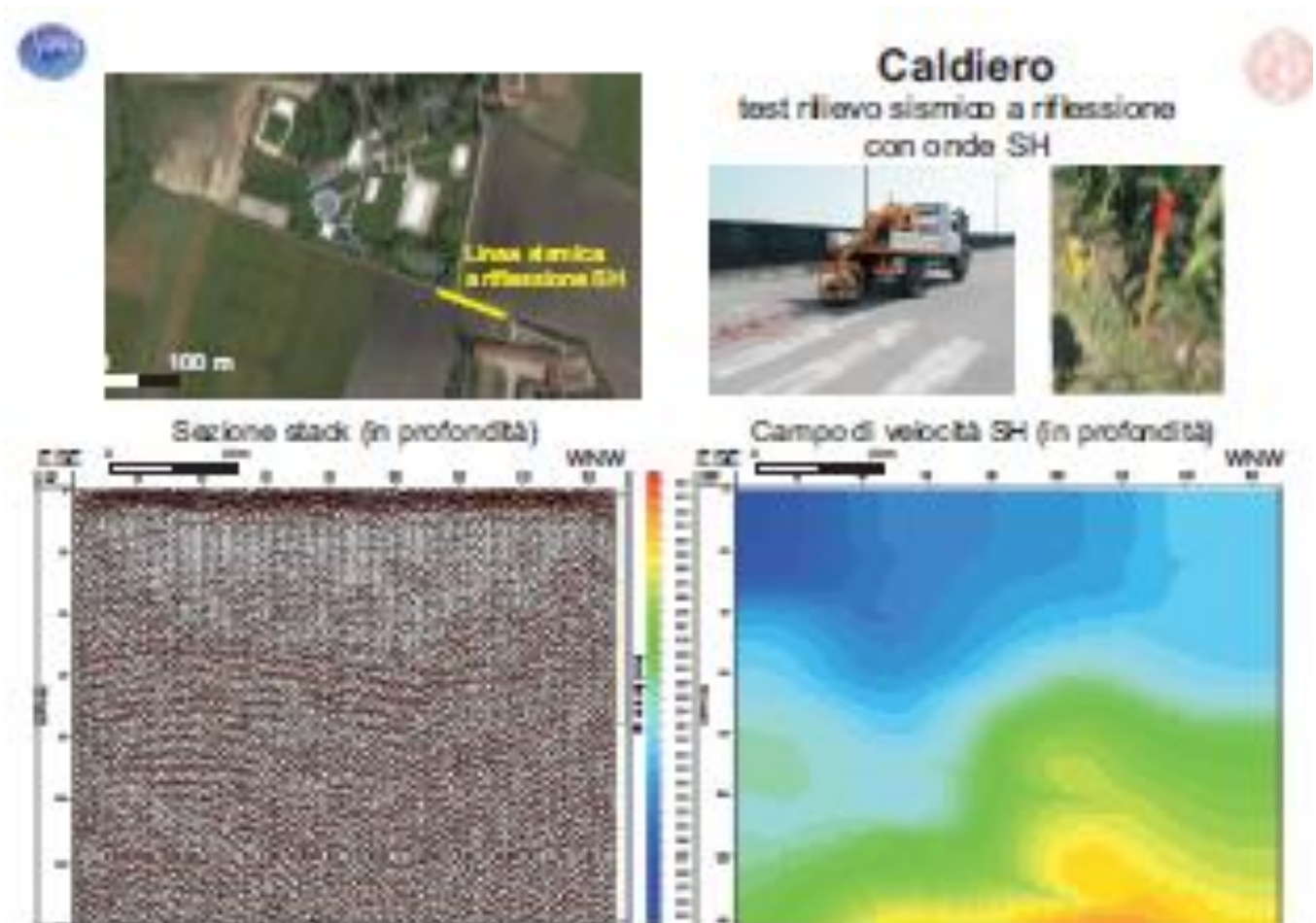


Fig. 6.2.3 – OGS survey

The results of these surveys helped define with more precision the origin of the rise of water in that area. In fact, with seismic reflection, there is the trace of a possible fracture or more fractures that pass through the thermal area (Fig.6.2.1.1).



Afterwards a geo-statistical analysis was applied to seismic noise measurements in the framework of a thermal basin characterization. The site test is located in the N-E part of Italy (Caldiero, Verona Province) where more than 100 passive single station seismic noise measurements were conducted. The final aim was the characterization of an important hydrothermal basin, which is exploited since the Roman Period. The huge amount of measurements offers high density cover, since the measurements point has average spacing of 100 m for a total area investigated of ca 100ha. The HVSR (Horizontal to Vertical Spectral Ratio) is a geophysical passive technique used to retrieve fundamental resonance frequency of the subsoil. The measurement consists in passive recording of seismic noise with 3 components broadband receivers. From the spectral analysis of the recorded data, we can retrieve the resonance frequency of soil and hence information about depth and mechanical properties of soil covers. Since HVSR is a punctual measurement, 2d map of the results are usually extracted with interpolation procedure, as common kriging or natural neighbor techniques. Despite this accurate statistical procedure are rarely adopted for HVSR analysis, limiting the real significance of the dataset. As a matter of fact, rigorous statistical approach of the spatial distribution is neglected in common HVSR geophysical prospecting. Here we present the use of advanced spatial-statistic technique (e.g. cross-validation, residual distribution etc.) applied to HVSR

data. Our results show as critic data scrubbing, joined to rigorous statistical approach for data interpolation, are mandatory to assure meaningful structural interpretation of microtremor HVSR survey. The maps obtained are compared with boreholes data, reflection seismic prospecting, and geological information. The proposed procedure highlighted the potential of these quick passive measurements, if correctly treated from the statistical point of view (Boaga et al., in publication).

## 6.2 Lake Garda Thermal Water

The basin occupies a deep fluvial valley originated during the superior Miocene (5-6 million years B.C.) modified during the successive Quaternary glaciations. The main morphometric and hydrological characteristics of Lake Garda and its basin are summarized in Tab. 1.

The catchment of Lake Garda is relatively small in relation to the lake area (6:1) considering its low ratio of catchment area to lake volume and its low annual rainfall and compared with the other deep southern subalpine lakes, Lake Garda has a long theoretic water renewal time of 26.6 years (IRSA 1974).

Tab. 1 Morphometric and hydrological characteristics of Lake Garda and its basin.	
<b>Basin</b>	
Surface area (SB)	2290 km <sup>2</sup> * - 2350 km <sup>2</sup> **
Max. elevation P	Presanella Mountain
Max altitude	3558 m a.s.l.
Main tributary	River Sarca
Mean outflow discharge of the main tributary	30,5 km <sup>3</sup> s <sup>-1</sup>
Main emissary (the only)	River Mincio
Mean outflow discharge of the emissary	58,4 km <sup>3</sup> s <sup>-1</sup>
<b>Lake</b>	
Surface area (SL)	368 km <sup>2</sup>
SB/SL ratio	6,2 * - 6,4 **
Perimeter	165 km
Sinuosity index	2,43

Max lenght	51,9 km
Max width	16,7 km
Max depth	350 m
Mean depth	133 m
Latitude	45°42 'N
Longitude	10°43 'E
Surface elevation	65 m a.s.l.
Water volume	49031 10 <sup>6</sup> m <sup>3</sup>
Renewal time	26,6 y
Thermal classification	warm monomictic - oligomictic
Trophic classification	oligo-mesotrophic

Lake Garda is north–south oriented. On the basis of bathymetric values, Lake Garda can be divided into two basins separated by an underwater ridge connecting the Sirmione peninsula with Punta S. Vigilio (Fig. 2).

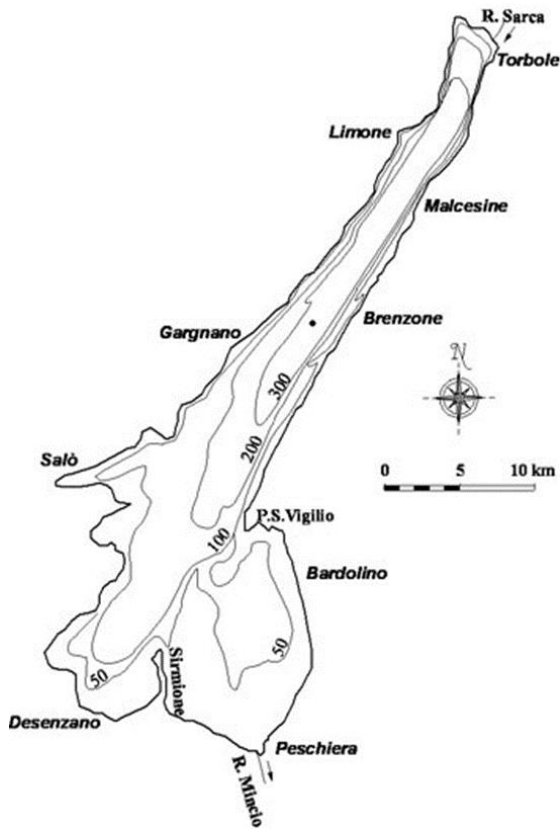


Fig.7.2- Bathymetric map of Lake Garda (Barbanti, 1974 modified by P...)

The western basin is the larger and deeper of the two and can be further in northern and southern basin. Its northern part, the shores are steep and the bottom extends for 20 km at depths ranging from 300 m to 350 m. The shallower eastern basin has a maximum depth of 81 m and represents only a small portion of the lake's overall volume (0,7%).

The water balance of the Lake Garda calculated according to the amount of the inflowing water (River Sarca water + rain water on the lake, + 20% of the precipitations on the whole catchment basin) and to the amount of outflowing water (River Mincio) showed a large imbalance, with the river outflow alone resulting on average, during the last decade, at least double the inflow. To explain this imbalance of the lake, a large recharge by concealed groundwater is suggested. Lake Garda is classified as oligo-mesotrophic with total phosphorus (TP) values of around 20 µg/l. During the last 35 years, there was a significant increase in phosphorus content but since 2006 total phosphorus concentrations seem to be stabilized. The concentrations of ammonia nitrogen (NH<sub>4</sub>-N) in the euphotic layers affected by algal production (ca. 0-20 m) and in the hypolimnion generally have values less than 25 µg N l<sup>-1</sup>. Similarly, nitrous oxide (NO<sub>2</sub>-N) is always present at concentrations generally less than 10 µg N l<sup>-1</sup>. Chlorophyll-a concentrations exceed 8 mg/m<sup>3</sup> only during some spring algal blooms.

The mixing processes have a significant impact on the evolution in time of the concentrations of dissolved oxygen and nutrients. During the years of full circulation, there is an higher concentration of nutrients in the surface water (negative effect) as well a good oxygenation of the deep water (positive effect). This last process limits the release of phosphorus from the sediments and that favours the processes of mineralization of organic matter. Generally after the full circulation the

higher concentration of nutrients causes a greater algal development and a consequent increase in chlorophyll.

### *The Thermal Field 2015*

The Thermal field 2015 together Perla Project\_2010 are important projects regarding the tectonic structural situation of Southern Lake Garda.

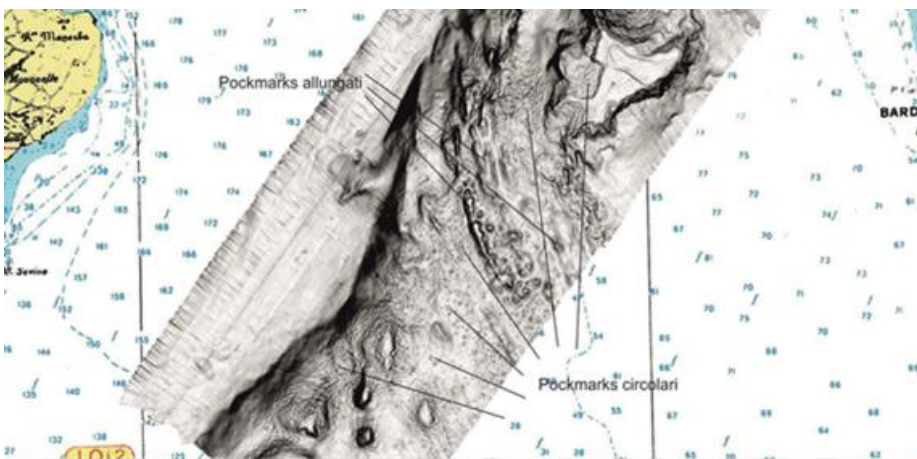
This part of Lake Garda is crossed by San Vigilio-Rivoltella-Sirmione fault that runs on the South extension of the Monte Baldo thrust. The fault plane is outcropping in Sirmione, but the structure is evident also on the shores near San Vigilio and Rivoltella, and offshore. The Sirmione peninsula, in the southern part of Lake Garda, is linked by a bridge. Sirmione conglomerates, middle Pleistocene age, new datation in Scardia et al., 2012, and Cretaceous marls are overlapped by a NE –trending reverse fault with a displacement in the order of hundreds of meters, but other several secondary faults offset the bedrock.

The Quaternary activity of the San Vigilio-Rivoltella- Sirmione fault is attested at several sites (Berlusconi et al., 2013):

- the morphology of the Sirmione area shows scarps in Quaternary deposits that clearly intelligible through airphoto interpretation, parallel to the fault planes, suggesting a possible recent activity;
- hydrothermal springs are present on the eastern side of the peninsula (see Bojola spring in the Lake);
- the abrasion platform around the peninsula is tilted and deformed, with the North sector at least 1 m higher than the S one (Castaldini and Panizza, 1991);
- on the hill immediately West of Rivoltella, morphologic saddles and fluvial elbows that could be related to a fault active during the Quaternary are described;
- ENI E & P seismic reflection profiles running near the town of Lonato del Garda, show a clear displacement of the Quaternary sequence (Rogledi, 2010);
- along the slope of Monte Luppia, glacial deposits lean to a shallow-water Jurassic limestone (San Vigilio Oolites (Barbujani et al, 1986), through a NW-trending and subvertical normal fault (Carton and Castaldini, 1985; Castaldini and Panizza, 1991). This can be interpreted as a secondary fault

possibly related to SSR fault, or eventually as a deep seated gravitational movement. The off shore extension of the Monte Luppia Fault strand can be recognized in bathymetric data (MF in Fig. 7.1);

- abrasion platforms, 8 to 12 m lower than present lake-level, are reported (Baroni, 1985) in the hangingwall sector of the Monte Luppia fault, suggesting a Holocene reactivation of this structure;
- high resolution shallow seismic reflection profiles in the SE of Lake Garda area (Curzi et al., 1992), see Fig. 7.1, show normal faults in the lacustrine sequence and a gentle bending of Holocene sediments leaning on the scarp imaged;
- near Venzago, S of Desenzano, Quaternary N-verging folding in a gravel and sand quarry, is interpreted



(see Castaldini and Panizza, 1988) as a glaciotectonic feature, or as a local deformation not related to tectonic activity.

### Perla Project 2010

The article “Quaternary Faults and Seismic Hazard in the Lake Garda Area”, Berlusconi et al., 2013, describes a research carrying out between localities of Sirmione and Punta San Vigilio in the Lake Garda.

A morphobathymetric cruise, in fact, was conducted, in 2010, by a conjoint team of University of Insubria, CNR-IACM and with the collaboration of INGV, Guardia Costiera, Comunità del Garda, and Geomarine s.r.l. Senigallia Ancona.

The purpose of cruise-research aimed at collecting multibeam data and analyzing morphological features related, if possible, to recent offshore surface faulting and deformation. This study was completed by geophysical, geological, geomorphological and historical analysis.

The ship was equipped with a multibeam system which uses echo sounders to reconstruct a 3D model and with a Side scan sonar. In this way data processing produced a Digital Terrain Model (DTM) of the lake floor with a resolution of 2 m, where it can be identified two areas with different morphological features.

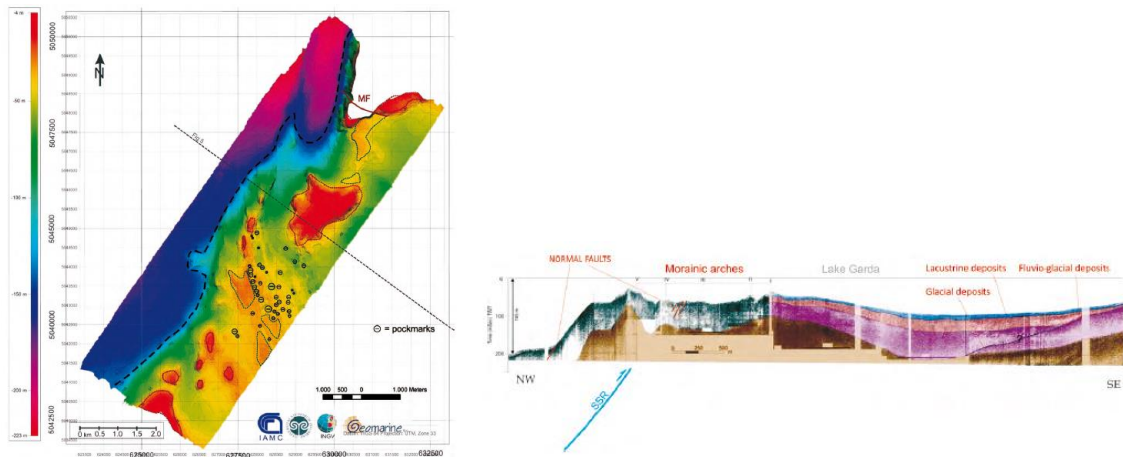


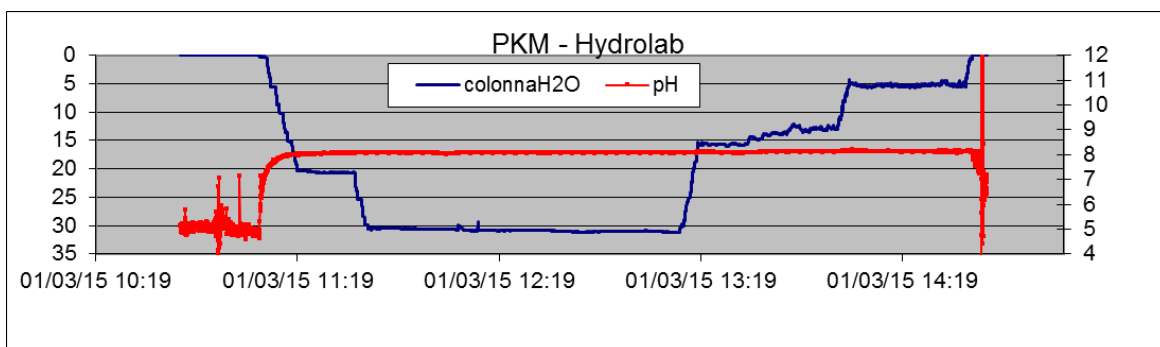
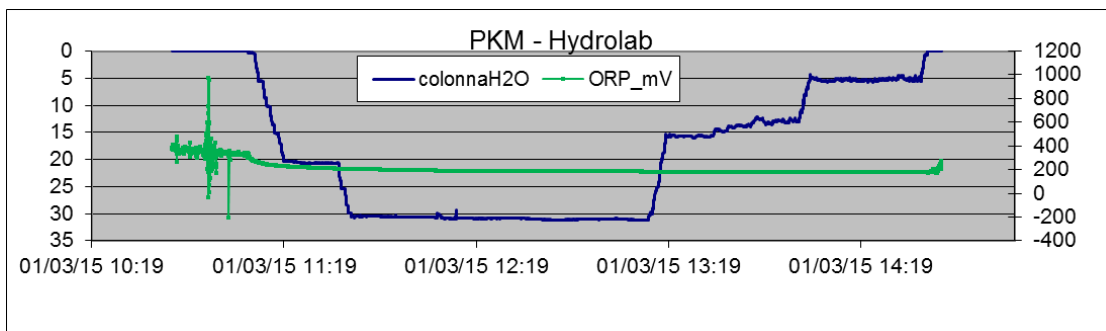
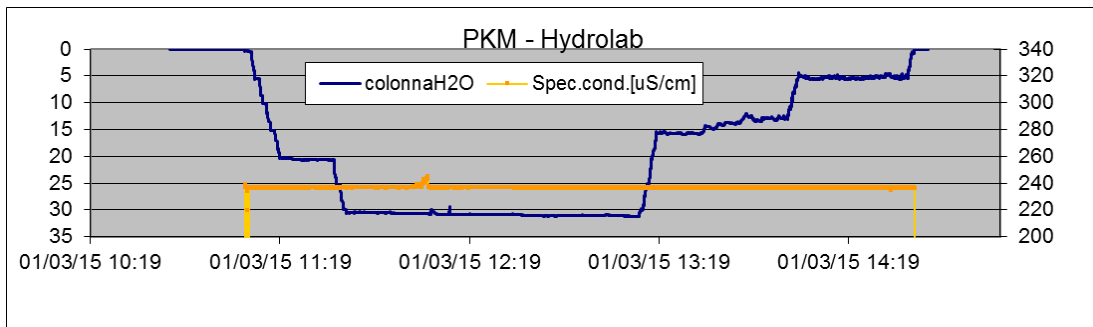
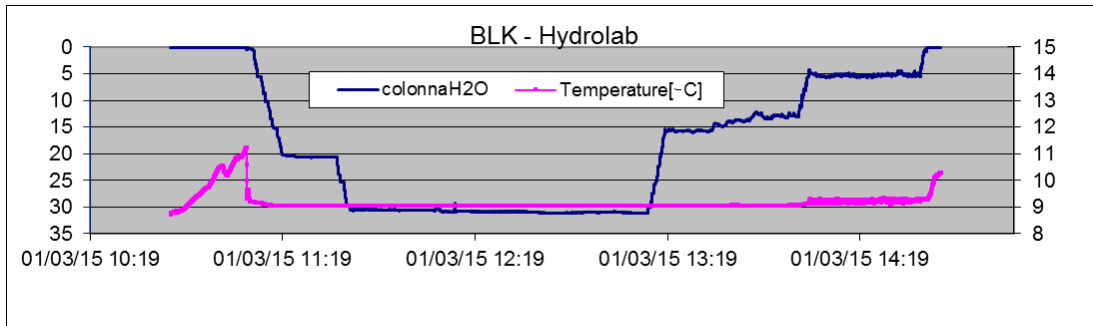
Fig. 7.1 Morphobathymetric map of the Punta San Vigilio-Sirmione structural high along the San Vigilio-Sirmione-Rivoltella fault. Data processing shows a complex morphology influenced by fluvial and glacial erosion and deposition, and by Quaternary tectonics. Dashed black line divided the NW flat sector (-150 m deep) from the SE sector (-40 m deep). Green dashed line border the -30 m deep abrasion platform and the red dashed line the -5 m abrasion platform. MF: Monte Luppia Fault

1. The SE sector, San Vigilio-Sirmione high, lays between -3, 6 and -50 m in depth. It is characterized by glacial shapes and pockmarks fields perhaps referred to geothermal circulation.
2. A straight scarp is visible with a direction NE-SW, between the depth of -50 and -200 m.

### *A new research in Lake Garda*

In 2015, as further analysis are necessary to confirm or exclude a neotectonic genesis for these features, a new research was carried out by Department of Geoscience (UniPD), IGG-CNR of Pisa, University of Insubria with collaboration of Capitaneria di Porto di Salò and Soccorso Alpino P.Civile Regione Veneto Gruppo Subacqueo. One of the aims was to explore new arises of thermal water from the lake bed. Along the fault Punta San Vigilio-Sirmione were taken samples of water and, data was collected with the multiparameter probe Idronaut System Ocean Seven mod.401.

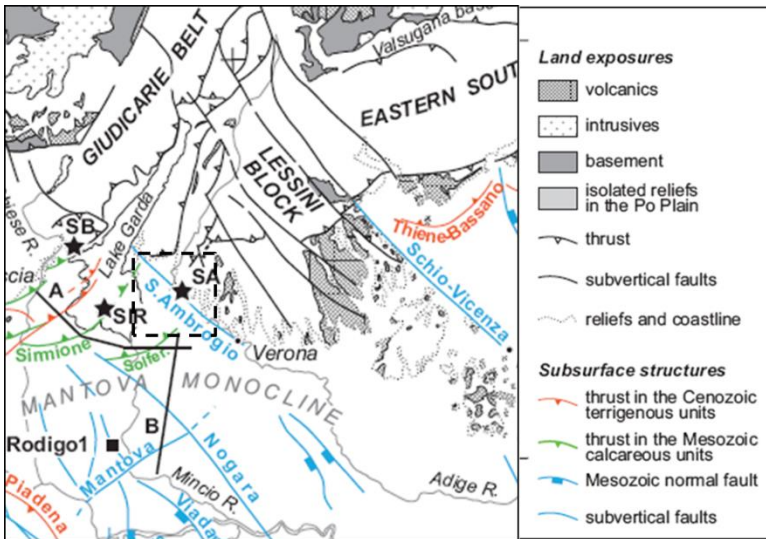
Unfortunately this analysis did not give important results, for the Bojola spring sampling whether for the relief of the backdrop.



Above the graphs show parameters of temperature, conductivity, ORP, and pH measured by the sensors and refer to the output of 1 March near of the Piana del Vo' in the Lake Garda (see photo by Google below).



### 6.3 Western Thermal Area



The western studied area is located in the eastern average sector of the Garda moraine amphitheater.

The localities with wells of warm waters (range temperature between 24-51°C) are: Sant'Ambrogio di Valpolicella, Pescantina, Domegliara, San Pietro Incariano,

Colà di Lazise, Piovezzano, Lazise, Castelnuovo del Garda, Peschiera, Bardolino.

The warm waters of these localities have a different salt content and isotopic informations.

For this motive we divided this area in two sections: the first, at Eastern, with a high content of Cl, and a good conductivity; the second, near to the Lake, with a minor temperature and a discrete Arsenic content.

The water containing the elements that collects during its path in the rocks and sediments hence, in the first case the path is short-direct deep from Lessini Mountains (see chapter 4), while in the second case the lacustrine sediments and moraine changed the original nature of water with different isotopic signals (see chapter 4).

We can see two different geological situations between the E area and W area.

Recent geophysical surveys evaluated a 140-300 m thick cover of glacial and fluvioglacial deposits. These surveys permitted to identify a structural high Giudicariense aligned with NNE-SSW direction and to locate the bedrock between -400 m from ground level in Piovezzano and -500 m g.l. in Colà di Lazise (Castellaccio and Collareda, 2013).

These conditions would be favorable to a rapid outflow of hot fluids from carbonate bedrock basement spreading gravel permeable sediments that are below the glacial deposits (Scardia, 2015).

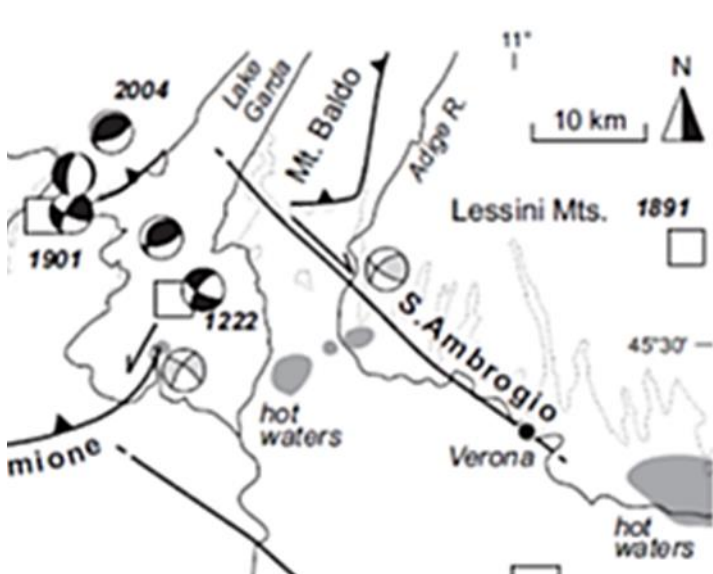
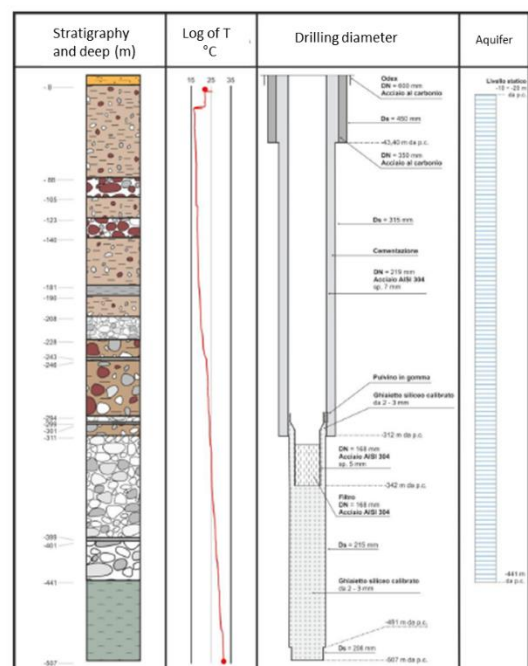
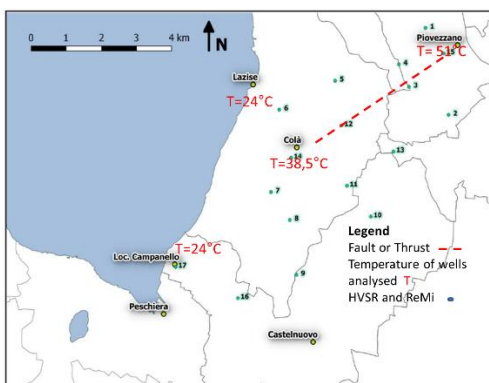


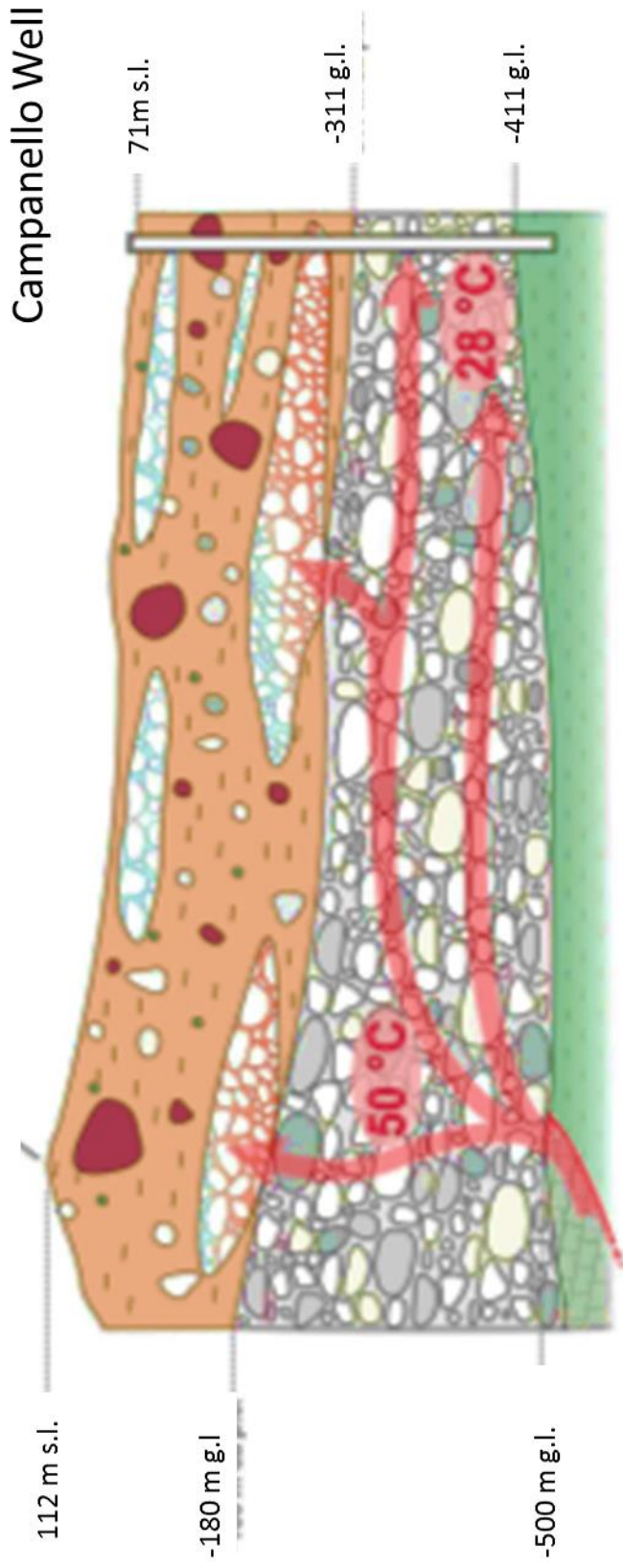
Fig.6.3 In figure seismotectonic map with signed hot waters areas in Verona Province (Scardia, 2015).

In this context the hypothesis of a warm water circulation could be very different. In fact glacial and fluvioglacial deposits cause, a short distance, a sudden change of permeability, influencing the vertical and horizontal circulation of the thermal waters from bedrock.

The ascent of warm water seems to be favored by the presence of transversal dislocations due to strike slip faults of the system Schio-Vicenza that upward movement of water allowed (see Fig.5.4 Posenato, 2015).



### Colà di Lazise



### LEGEND:

	Glacial deposit		Marine deposit
	Fluvio-glacial deposit		Marl clay
	Alluvional deposit		Limestone

## Chapter 7

### Discussion

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The study extends along the southern boundary of the Alps, mostly within the Verona and Brescia provinces (north-east Italy).

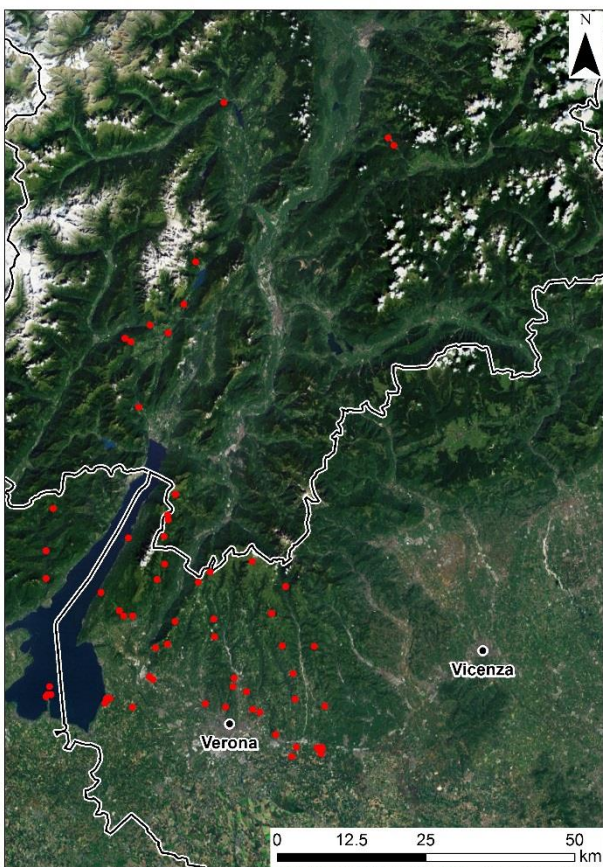


Fig. 7.1 In photo thermal wells studied

In order to define the characteristics of the warm and hot waters between the area of Sirmione and Caldiero, their origin and path in the subsoil, the research was extended in an area of about 5000 km<sup>2</sup> including the Trento Province. The eastern plain thermal district is mainly around the little town of Caldiero, but it also includes the municipalities of Belfiore, Colognola ai Colli, Lavagno, S. Martino B. A., S. Bonifacio, Zevio, Ronco all'Adige and Arcole. In this area, the temperature of the fluids fluctuates between 15 °C and 31 °C. Those peculiar hydrogeological

characteristics allow conditions of flowing artesian phenomena and the emergence of the ancient springs of Brentella and Cavalla in Giunone spa, the only thermal groundwater emergences of the province of Verona. The other thermal district, that we can generally call northern plain thermal district, is divided into two different areas. The same hydrogeological conditions define the eastern part of this district, which includes the thermal field of the municipalities of the towns of Sant'Ambrogio di Valpolicella, San Pietro in Cariano and Pescantina. The western part includes the

morainic area thermal fields of the towns of Pastrengo, Lazise, Bardolino, Peschiera and Castelnuovo. This district spreads between the towns of Sirmione (BS) and Sant’Ambrogio di V.Illa where the highest subsoil water temperature decreases from West (about 70 °C) to East (46 °C). Reports of wells showing thermic anomaly at low thermalism (15 °C - 22 °C) are rare outside the thermal districts which are considered more reliable for warm water discoveries. This situation proves the vast extent of the hydrothermal system and the existence of complex hydrogeological phenomena which causes the fluid movement.

In the alluvial zone of the province of Verona the subsoil lithological and hydrogeological situation has been studied using seismic geophysical methods. This tool allowed me to investigate the area around the spa Caldiero, determining, with the help of the stratigraphy of some wells, the substrate. To further definition of the substrate, the use of geoelectric surveys NS and EW direction was planned (OGS Trieste). This research could highlight volcanic chimneys such as, Mount Gazzo and Mt Rocca, near Caldiero spa, may be preferential ways for the ascent of hot water (Canatelli, 2011; Galgaro et al., 2013). At the same time by the help of statistics program we tried to relate the rainfall in the hilly north of Caldiero with the reach of more than 10 years of Brentella well, well spa town, but it did not give any significant correspondence.

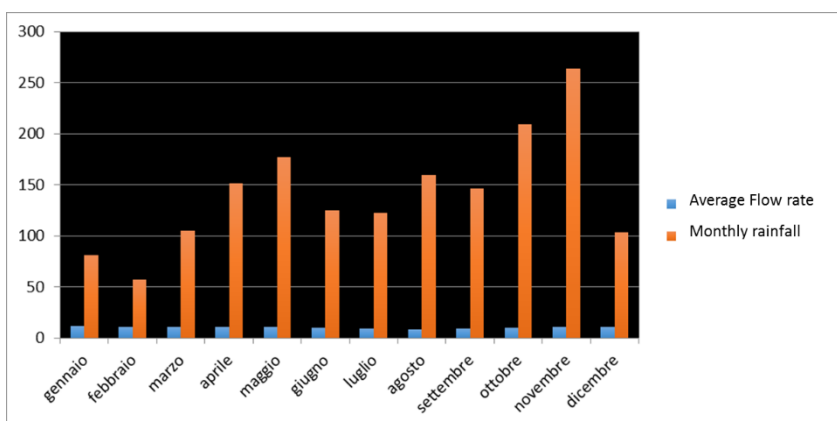


Fig.7.2 Brentella well rainfall/flow rate

After analyzing approximately 1000 wells in the studied area and sampling 72 important sites between warm and cold spring- well water, we have to define the origin of such water, and then the traffic routes. To create a model of movement it’s necessary to make isotopic analysis. The thermal

samples was only 16 because some owners of spas do not agree to give permission to take samples.

The analysed samples, the geological and tectonic research of territory and the history data collected, lead to some important considerations about the origin of the thermal water in the study area.

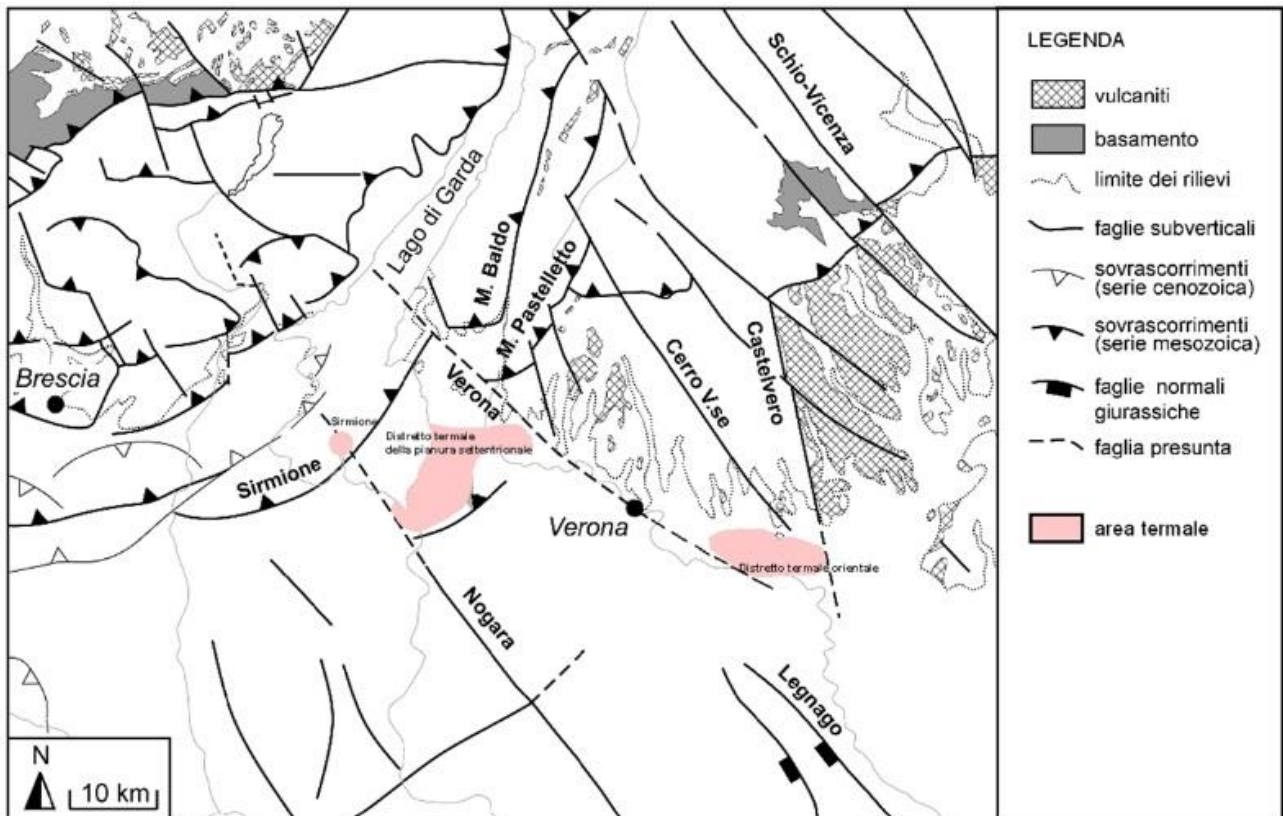


Fig. 7.3 Faults with thermal area in Verona Province (Scardia, 2012)

In fact, from the analyses data I saw that the salt content in thermal water depends on different factors and it tends to increase as long as the fluids flow underground, whilst its chemical composition is influenced by the rock types with which the water comes in contact (see 5.3). As long as the temperature increases the thermal waters get less sweet but slightly brackish. Sulfates are a result of the exchanges with the deep rock reservoir characterized from mineral evaporitic origin (dolomite and limestone dolomitic), while a study conducted in the nineties showed that there were processes of limestone dolomitization during volcanic activity of Tertiary Veneto. The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio samples of Mesozoic dolomitization limestone analysed in this research (Cervato, 1990) is similar to  $^{87}\text{Sr}/^{86}\text{Sr}$  found for thermal water samples (see 5.3.3).

The chlorides may be related to the presence of marine origin sedimentary rocks which are not fully consolidated and still containing brackish water as Pliocene-Pleistocene clays of Lazise area. While in Sirmione, as the bedrock is consolidated, must seek the contribution of chlorine in another geological context. The cold waters in the Veronese area are quite homogeneous in their chemical composition, and they belong to the single sulfate- bicarbonate-alkaline earth family in which the most significant chemical changes in thermalized water concern mainly about their total salt content, their composition, and in particular the anionic bicarbonate / sulfate + chloride ratio.

The hydrochemical survey allowed to classify the thermal waters of the Caldiero using the Piper diagram (see Chapter 4). In the Eastern Plain Thermal District warm waters are calcium-bicarbonate, almost sulphate with a modest amount of alkalis (Na + K) but with significant quantity of magnesium. Thanks to their chemical nature these waters belong to the bicarbonate-calcium-magnesium primary alkaline-earth facies, secondary sulphate-calcic facies. In the thermal areas of research from the analysis carried out, it is remarkable that the TDS is greater than about twice the east than in the west of Caldiero. This is due to the temperature of 26 °C degrees Caldiero compared to the 42-52 °C area of Piovezzano-Sant'Ambrogio di Valpolicella to the west. That means that the circulation and transition in the rocks are different. By means of the few analysis performed and based on the historical ones we can assume two different types, or more, of thermal groundwater.

To understand the origin and a circulation of water in the substrate, the first step was to relate all data analysed of thermal waters chemical samples and historical ones with isotopic data collected in the laboratories of the CNR of Padua and Pisa. The values of  $^{87}\text{Sr}/^{86}\text{Sr}$  of carbonate rocks provide in Cervato and Mullis (1992) are very similar compared with those of the analysed thermal waters (see Table in Appendices and in Chapter 4) and they suggest an interesting hydrothermal model.

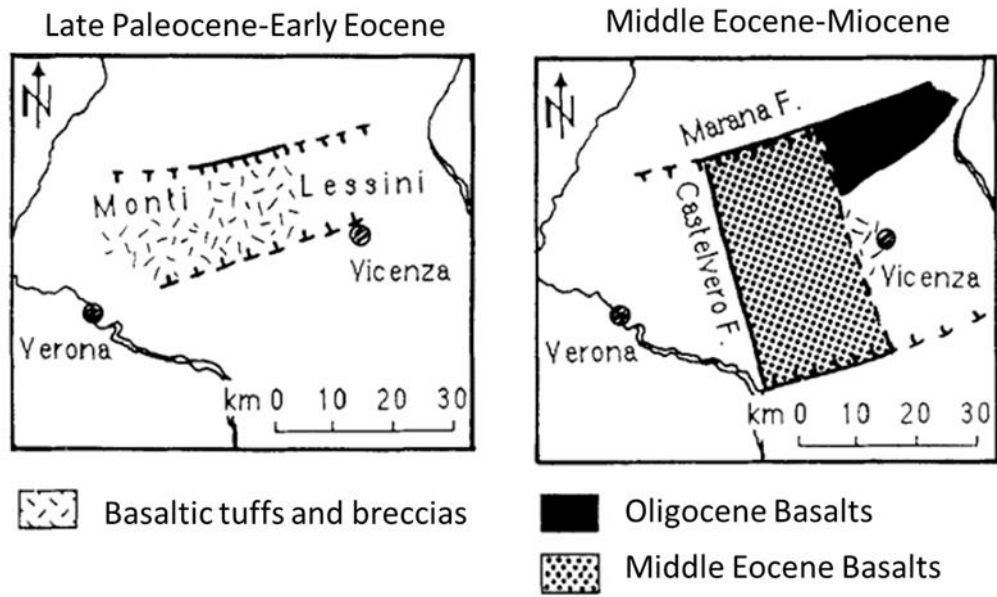


Fig. 7.4 Tectonically controlled distribution of basaltic rocks in the Lessini Mountains in the Tertiary (citare la fonte della figura)

The dolomitization of the Lessini Mountains is the product of a Late Oligocene to Early Miocene hydrothermal activity that affected the Jurassic to Cretaceous sedimentary series. The flow of water through the dolomitized limestones allowed us to explain the values of the ratio of  $^{87}\text{Sr}/^{86}\text{Sr}$ , which otherwise would be discordant with the geology of the study area.

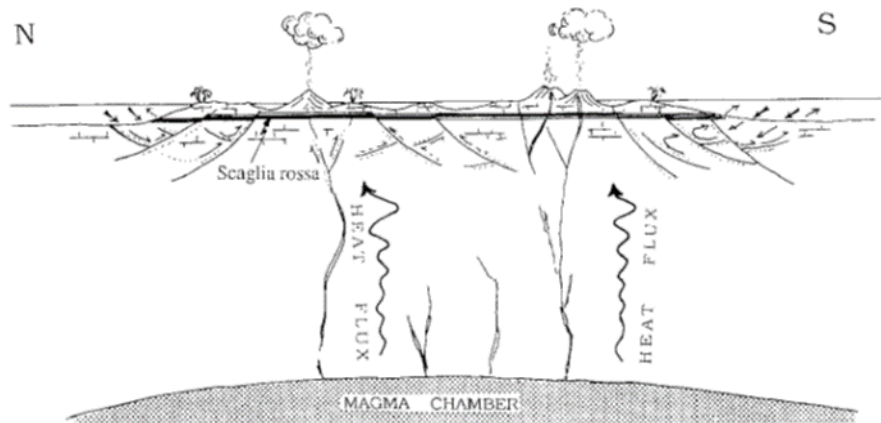


Fig. 7.5 Hydrodynamic model proposed for seawater circulation in dolomitized area during Late Paleogene. Platform was about 50 km wide. Height is exaggerated (Cervato, 1990)

Favorable chemical conditions related to structures and lithology led to the formation of the thermal water. To understand how the hydrological/thermally induced model occurs, it is necessary to firstly

explain how to locate the origin of infiltration water. The chemical and physical conditions of the origin of the examined water have been suggested in accordance with the data obtained (see Chapter 4 - D,  $^{18}\text{O}/^{16}\text{O}$ ). There are two factors still necessary to complete the definition of circulation water model: the limestones permeable to the fluids and the deep circulation of the water in the layers.

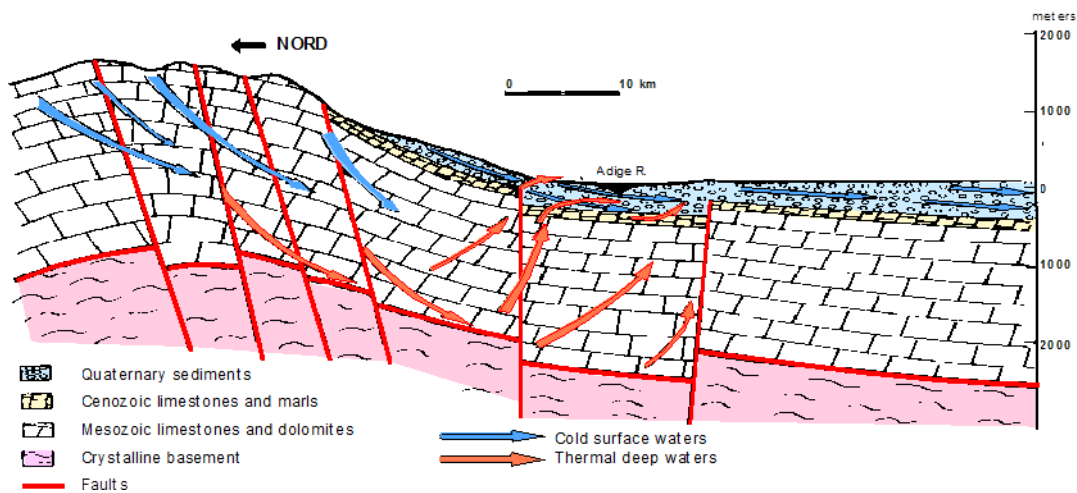


Fig.7.6 Section of thermal Veronese area (Sighinolfi et al., 1982)

The first part of the problem is quite easily resolved, taking into account the field observation of the stratigraphic conditions: the limestones are intensely fractured, and karstified with a discrete porosity. In the presence of an adequate fracturing, the fluids would flow along distinct pathways, generated by the action of extensive tectonic disturbance, as Sirmione, Verona and Sant'Ambrogio faults, and volcanic previous activity. The flow of fluids through these tectonic channels also it allows the rapid ascent of hot water with the consequent appearance of springs (e.g Brentella, Cavalla, Bojola). In this situation we can say, based on historical and laboratory data that the Eastern thermal area shows a thermal circuit quite limited where the waters seep about 30-40 km North on Lessini Mountains, about 1000 meters, and penetrate in the substrate warming for thermal gradient.

Then it find a preferential way of lifts in an area intensely fractured by the presence of two mountains in the area whose origin is volcanic. Because the Caldiero area is heavily fractured and faulted, the thermal water rises and mixes in alluvial with colder aquifer.

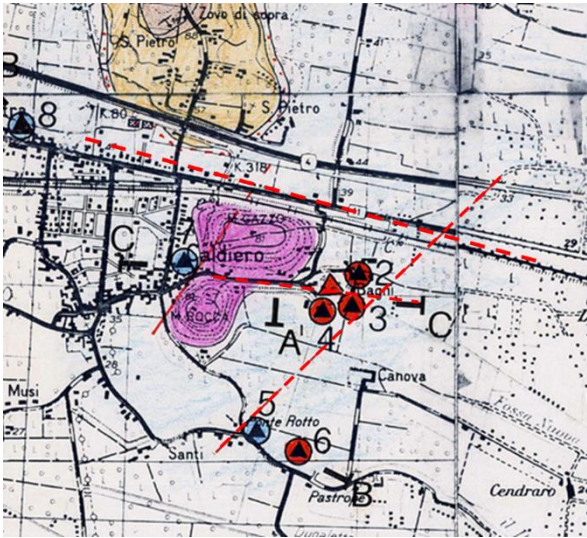
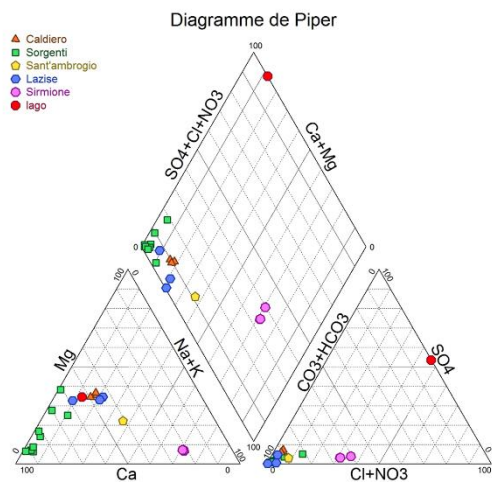


Fig. 7.7 In the map some wells sampling in red warm water, in azure cold water (circle shape), and warm spring with a triangle shape (red colour). In evidence, with purple color, Rocca and Gazzo Hills (basalt hills) and San Pietro Hill in brown colour (basalt rock). The faults, signed in red, permitted the ascent of water in that point.

Fig. 7.8 Section of a digging for a new swimming pool in Caldiero spa. It is visible a basaltic layer and loess layer (Meneghel, 1982) below alluvial sediments (thick 3 meters). Below Piper Diagram (in circle red Caldiero water analysis)



Although the area of infiltration is always localized on North Lessini Mountains, share about 1500-1700 meters (M.te Tomba and Corno d'Aquilio) the path of western

thermal water is short and deeper than Caldiero thermal area.

This can be seen from the chemical and isotope data. The quantity of chlorine present in the wells of SAV and Pescantina shows that a deep-slow path, but affinity with thermal water of Eastern thermal area. A common important factor is the amount of sulfate present in both the thermal area which highlights two possibilities: the first caused by an interaction long the Verona fault finding here a preferential lifts with direction NW-SE; the second caused by a path N-S of water where both

thermal waters meet and leaching the Bellerophon Fm (Trias), which crops out around Recoaro and Trento. The thermal water of the Lake Garda (Lazise, Peschiera, Castelnuovo) has a probably origin from the infiltration water of the Baldo but is mixed and polluted by lake sediments and peat layer.

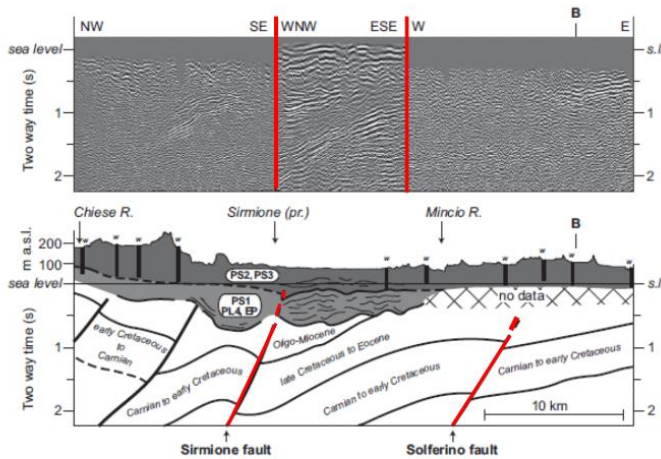
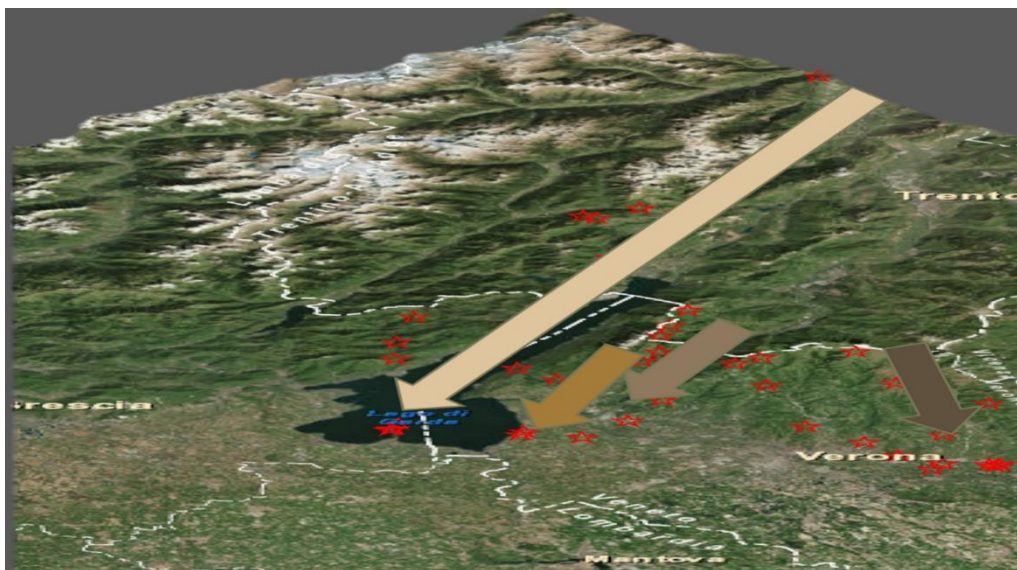


Fig.7.9 Section of Lake Garda area (Scardia, 2015)

Sirmione circulation type, a carbonate reservoir, is different. It is contained in the pre-Quaternary rock of the plain and the deep where there is intense hydrothermal fluid movement with little or no connections with the cold surface water systems. The Sirmione thermal water is characterized by a high sodium/ chlorine content and presents similar isotopic ratios with very high altitudes of infiltration. Unlike what was thought the circulation of this water is very deep and long, probably its origin is on Brenta Mountains in Trentino area or, perhaps, further north (samples TN and LAC). The tectonic situation, in this area, is very complex as it can be inferred from the figures relating to the benacense and to Sirmione area.



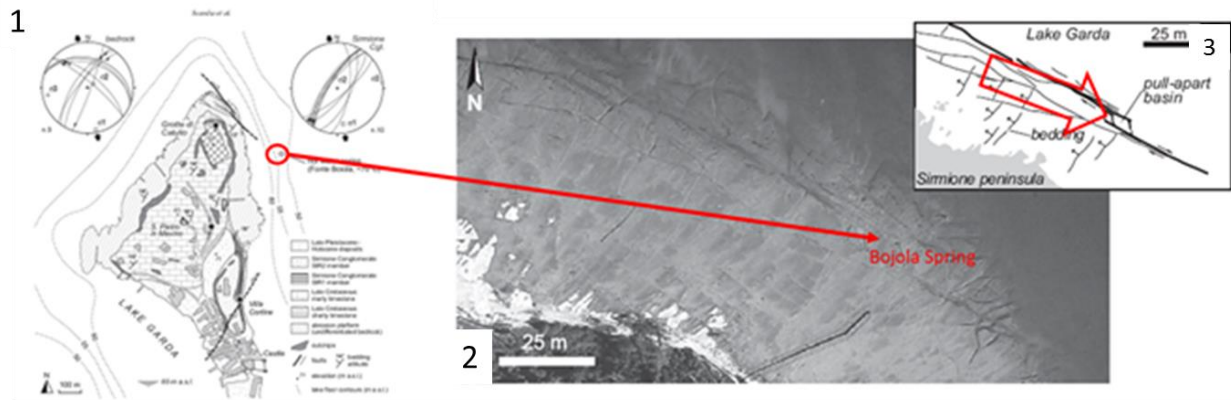


Fig.7.9 Evidence of tectonic deformation in the Sirmione peninsula: (1) Left-lateral, NE-striking, high-angle fault zone at Villa Cortine, consisting of several-meters-long anastomosed faults (blank lines) and depicting small-scale flower structures (hammer as scale). Secondary extensional component of movement is shown by the displacement of bedding surfaces (dashed white lines). (2) NE-striking and left-lateral fault, consisting of a decimeters-wide shear zone internally characterized by anastomosed fault surfaces (Villa Cortine locality). (3) Aerial photograph of the northern end of the Sirmione peninsula, showing, strike-slip fault system and the NNE-striking bedding attitude (Scardia et al., 2015, modified).

# Chapter 8

## Conclusion

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The PhD study, while requiring more detailed analysis and in-depth, goes to fill a gap in understanding the thermal phenomenon of Verona-Lake Garda area, allowing to make an important contribution to a process of sustainability analysis of the current use of the resource, its further development, and to its protection.

We can therefore say, as closing statement of this work:

- ✓ the intergrated geological, geophysical and geochemical research here is characterized by different temperatures and hydrogeological conditions with typical circulations in carbonate formations; the new available data suggest, on one hand the wide extent of the hydrothermal circulations and, secondly, the existence of a complex and differentiated hydrogeological framework;
- ✓ the produced data provide new insights into the framework of local thermal groundwater circulation;
- ✓ thanks to this study it was possible to identify three main hydrothermal areas which have peculiar thermochemical features: the area of Sirmione-Lake Garda, the south-eastern sector (Lazise, Sant'Ambrogio di Valpolicella, Pescantina) and a larger eastern clearly differentiated by temperature and circulation type (Caldiero);
- ✓ chemical and isotopic analysis data highlight altitude of infiltration and which have been leached from the thermal waters the rocks; in particular, regarding the Sirmione thermal area, by means of the geochemical data with the geo-structural framework, it appears likely that a significant recharge of the geothermal resource originates on the Alps zone, more than 50 km north with altitude of about 3000 meters; the hydrothermal souces of Lazise-Sant'Ambrogio di Valpolicella-Caldiero waters, come from Lessini Mountains, more than 20 km north with altitude of about 1500 meters;
- ✓ the geothermometry indicates a deep circulation about 2,5 km (Sirmione area), 1,5 km Lazise- Pescantina Sant'Ambrogio areas) and 600 meters (Caldiero thermal area).

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# Appendices

## Section A

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### **Geostatistic applied to seismic noise measurements for hydrothermal basin characterization**

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We present a geo-statistical analysis applied to seismic noise measurements in the framework of a thermal basin characterization. The site test is located in the N-E part of Italy (Caldiero, Verona Province) where more than 100 passive single station seismic noise measurements were conducted. The final aim was the characterization of an important hydrothermal basin, which is exploited since the Roman Period. The huge amount of measurements offers high density cover, since the measurements point has average spacing of 100 m for a total area investigated of ca 100ha. The HVSr (Horizontal to Vertical Spectral Ratio) is a geophysical passive technique used to retrieve fundamental resonance frequency of the subsoil. The measurement consists in passive recording of seismic noise with 3 components broadband receivers. From the spectral analysis of the recorded data, we can retrieve the resonance frequency of soil and hence information about depth and mechanical properties of soil covers. Since HVSr is a punctual measurement, 2d map of the results are usually extracted with interpolation procedure, as common kriging or natural neighbor techniques. Despite this accurate statistical procedure are rarely adopted for HVSr analysis, limiting the real significance of the dataset. As a matter of fact, rigorous statistical approach of the spatial distribution is neglected in common HVSr geophysical prospecting. Here we present the use of advanced spatial-statistic technique (e.g. cross-validation, residual distribution etc.) applied to HVSr data. Our results show as critic data scrubbing, joined to rigorous statistical approach for data interpolation, are mandatory to assure meaningful structural interpretation of microtremor HVSr survey. The maps obtained are compared with

## Geothermalism in the Province of Verona

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Keywords: thermal springs, geothermalism, district, energy.

The authors, through analysis of several geological, chemical and historical data, studied the thermal waters of the province of Verona and provided new insights and interpretations on the hydrothermalism western of the Veneto, with the ultimate objective of permitting the rational use purpose energy. The preliminary research allowed to define areas of thermal springs divided into two main districts. Now it is possible to distinguish "hot areas" characterized by homogeneous geological and chemical conditions. The first district of the plain Eastern (A) is focused mainly in the neighborhood of Caldiero, but also brings together the towns of Belfiore, Colognola ai Colli, Lavagno, S. Martino Buon Albergo, S. Bonifacio, Zevio, Ronco all'Adige and Arcole. The temperature of the fluid takes on values between 20 ° C and 31 ° C and the peculiar hydrological conditions allow artesianesimo bubbling to the surface. In this area we can see the manifestation of the historical sources as Brentella spring. The second district, called District spa northern plain (B), distinguishes between two different sectors based on hydrogeological conditions: to the east, it includes the towns V.la Sant'Ambrogio, San Pietro in Cariano, Pescantina while, to the west, thermal fields are found in the moraines of the municipalities of Pastrengo, Lazise, Bardolino, Peschiera d / G. and Castelnuovo d / G. Including also Sirmione (BS) we can see that the temperature of groundwater is decreasing from west (about 70 ° C-Sirmione) to the east (46 ° C-S.A.V.). In Saint Ambrose of V.la water hot is been found in wells between -60 ÷ -130 m m from ground level while the temperatures vary between a minimum of 20 ° C to 46 ° C (Castellaccio & Zorzin, 2012). In the morainic, however, areas characterized by the presence of hot water at higher temperatures is between the villages of Colà di Lazise, Piovezzano and, especially, at around the same localities with the largest number of deep wells, ranging between -140 m and -240 m from the PC, with temperature values of water ranging from 35 ° C and 52 ° C. Outside the spa districts, considered most important for the discovery of hot water, wells are isolated reports of possible thermal anomaly (20 ° C to 22 ° C). This situation testifies, on one hand the vast extent of the hydrothermal system and, secondly, the existence of complex hydrogeological phenomena. In the context of the Padana Plain and other areas located at the edges of the central and southern Apennines and Calabrian arc-Peloritano exist thermal waters whose genesis is related to circulation of fluids within carbonate structural clusters heated the normal geothermal gradient. The geothermal mapping of the Italian territory for that type of thermal spas shows a potential huge and easily available, which include the areas between Sirmione and the Adige Valley and the wide area around Caldiero. The low enthalpy of Verona spa is therefore a possible important source of energy for public environments (residential, industrial, hospital, sports, etc.), agriculture (greenhouses for vegetables and flowers, drying, pasteurization of milk, hydroponics, etc.) or for breeding (itticoltura of valuable species, incubation of eggs and poultry) or as a result of the presence of hot fluids in a favorable salt content, for the development of wellness centers and balneotherapy.

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*HVSR technique in near-surface thermal-basin characterization: the example of the Caldiero district (North-East Italy)*

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# **THERMAL ANOMALIES AND GROUNDWATER CIRCULATION IN THE PO PLAIN: THE GARDA LAKE AND THE VERONA PROVINCE CASE STUDIES**

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In the Po Plain, located in northern Italy between the Alpine and Apennine mountain ranges, the presence of territories characterized by local temperature and heat flux anomalies, as the Southern Garda Lake and the Verona Province areas, is well known. The thermal energy here extracted mainly for recreational, medical and agricultural purposes undergoes dissipation, so an optimization of its use must be planned. In fact, the use of low and medium temperature geothermal resources enhances a sustainable development of the area, combined with a significant energy and cost savings, as well as a substantial reduction of greenhouse emissions into the atmosphere. To promote a proper use of geothermal energy through direct uses of heat and by coupling with heat pump systems it is essential to characterize the geothermal reservoirs involved, taking into account the local differences related to geological, hydrogeological and thermal features. Aim of this paper is to characterize the selected areas from a hydro-geothermal point of view.

At first, a review of the tectonic-structural model leads to a better comprehension of the interaction between geological model and groundwater circulation both in Southern Garda lake area and Verona Province. In fact, generally, the Po Plain younger terrains form the cover of thick reservoirs of fluids located in the underlying carbonatic formations. Subsequently, the processing of temperature data collected in duly selected wells shows, from one hand, the evidence of thermal anomalies, and, from the other, the assessment of the geothermal gradient. When values higher than normal ( $> 3^{\circ}\text{C}/100\text{ m}$ ) are detected, the geochemical-isotopic characterization of water samples allows to identify origin and age of groundwater (meteoric, marine or non-marine, deep fossil brines) and the mixing processes affecting groundwater circulation. Finally, the experimental data obtained can be used as input parameters in geothermal modeling, leading to refine the models to assess renewability and potential of the geothermal reservoir previously identified.

## B Geochemical Data

### 1. Sheet of sampling

Technical File			
CODICE PUNTO D'ACQUA:		TIPO: <u>POZZO</u> <u>SORGENTE</u> <u>TORRENTE</u>	NOME:
DATA, ORA			
E			
EVENTUALI NOTE SU CONDIZIONI ATMOSFERICHE:			
PROFONDITÀ FALDA DA BOCCAPOZZO:		ALTEZZA BOCCAPOZZO:	
		QUOTA PIANO CAMPAGNA:	
TEMP. ARIA (°C):	TEMP. ACQUA (°C):	pH :	CONDUCIBILITÀ: ( $\mu$ s/cm a 20°C)
ALCALINITÀ ( $\mu$ l HCl 0,1 N):		ANALISI QUALITATIVA AMMONIACA:	
		POSITIVA	
		NEGATIVA	
CAMPIONI PRELEVATI			
1 BOT. DA 1 LITRO T.Q. (ARPAT)	1 BOT. DA 125 cc T.Q. (CNR)	1 BOT. DA 500 cc T.Q. (CNR)	1 BOT. DA 50 cc F.A. HNO <sub>3</sub> 1:1 (CNR)
1 BOT. VETRO DA 125 cc A HCl 1:1 (CNR)			
NOTE (portata sorg., periodi utilizzo pozzi, elementi idrostrutturali d'interesse, ecc.):			

## 2. Table of the codes used for the sampling

Identification	LA, LB	TN, LAC	AT, CR, AB, BC, VC
Site	Verona Province	Trento, Bolzano Province	Brescia Province

## 3. Table of sampling water in field with multi parameter probe:

ID1	Sorg o Pozzo	maggio-sett	T °C	pH	DO%	DO ppm	µS/cm	TDS ppm	Salinità	Alc.ml
LA49	P	16-apr	17,23	6,7	146	14,86	419	210	0,23	15,8;16
LA50	P	16-apr	15,5	7,2	69,3	11,88	637	319	0,35	0
LAC3	S	11-giu	11,1							0
LAC4	S	11-giu	12,9							0
LB5	S	27-mag	8,94	7,37	75,3	7,69	296	148	0,16	0
LB7	P	18-mag	26,52	7	68,1	5,64	538	268	0,28	12,9;13,1
LB8	P	18-mag	28,16	7,29	53	4,04	610	305	0,32	11,8;12,2
LB17	S	31-mag	13	7,35	83	7,25	128	64	0,07	0
LB18	S	31-mag	10,86	7,15	66,5	6,57	310	155	0,17	0
LB19	S	31-mag	9	9,42	64,3	6,58	355	178	0,2	0
LB20	S	29-mag	10	7,97	62,5	6,55	367	184	0,2	0
LB21	P	28-mag	25	7,21	37,1	3,21	472	236	0,25	11
LB22	P	28-mag	65,5	6,58	19	1,19	3890	1945	2,15	13;13,2
LB22/1	P	28-mag	63	6,79	14,3	1,05	3637	1815	2,03	13,1;13,5
LB23	P	28-mag	68	6,55	21,7	1,42	4025	2012	2,24	11,2;11,5
LB24	P	28-mag	23,8	7,4	40,9	3,57	508	254	0,27	12;12,2
LB25	P	28-mag	22,1	7,06	54,6	4,89	584	292	0,31	12,1;12,4
LB26	S	27-mag	18,3	7,3	73,4	5,97	519	260	0,28	0
LB29	S	29-mag	12,24	7,95	67,9	7,20	297	148	0,16	0
LB30	S	29-mag	11,4	7,9	55,3	5,45	345	173	0,19	0
LB32	S	29-mag	secca		0	0,00				0
LB33	S	29-mag	9,3	7,88	64,4	6,45	198	99	0,11	0
LB39	S	27-mag	17,7	7,49	56,1	4,40	245	122	0,13	0
LB40	S	27-mag	13	7,05	49,3	4,88	484	242	0,26	0
LB41	S	27-mag	13,5	6,9	111	11,08	469	234	0,26	0
LB42	S	27-mag	14,2	7,06	133,6	13,52	378	189	0,21	0
LB46	S	28-mag	58	6,69	32,4	2,22	3859	1932	2,14	
LB51	P	18-mag	27,3	7,17	51,4	3,80	561	281	0,29	9
TN1	S	28-mag	27	no data						7,2;7,6
TN2	S	28-mag	6,5	no data						0
TN7	S	28-mag	9,8	no data						0
TN1	S	25-giu	26	7,47	88,8	6,81	304	152	0,16	7,8
TN4	S	25-giu	7	7,66	150	18,02	145	73	0,08	0
TN5	S	25-giu	10	8	114,2	12,56	237	118	0,13	0
TN11	S	25-giu	3	9,13	129,3	13,39	141	71	0,08	0
TN12	S	25-giu	2,21	7,4	135,7	14,49	133	67	0,07	0
TN13	S	30-giu		no data			0	0	0	0
LA7	P	09-lug	26,7	6,9	124,4	9,62	507	253	0,27	9,9;10
LA10	P	14-lug	42	7,11	82,1	5,12	947	473	0,49	7,7;8,4
LA13	S	15-lug	14,4	7,29	98,3	12,18	338	168	0,18	15,4;15,9
LA23	P	14-lug	67	6,5	73,8	4,34	3796	1900	2	11,9;12
LA37	S	12-lug	14,3	7,5	128,4	12,41	437	218	0,24	0
LA43	S	12-lug	14,1	7,37	128,5	13,27	343	172	0,19	0
LA46	P	15-lug	57	7	52,6	3,20	3776	1886	2,08	10,5;11,7
LA48	P	19-lug	26,6	7,05	136,1	10,94	552	276	0,29	9,9;3
LA52	S	28-giu	7,53	7,03	72,2	7,47	242	121	0,13	0
LA53	P	14-lug	30,54	7,56	99,9	7,30	800	400	0,42	7;7,2
LA54	P	14-lug	15,1	7,3	86,1	8,73	547	274	0,3	0
CR1	S	17-ago	12,5	7,17	102,5	9,30	249	125	0,13	9,9;5
AB1	S	17-ago	10,5	8,03	85	8,91	299	149	0,16	0
BC1	S	17-ago	19,33	7,69	72,2	7,33	267	134	0,14	0
VC1	S	17-ago	18	7,62	87,6	8,34	434	217	0,23	0
AT1	S	17-ago	16,5	7,7	88,1	8,95	472	236	0,26	0
LA23	P	20-ago	65	6,67a 40°C	60,1	5,51	2986	1495	1,65	11,8;12,1
LA46	P	20-ago	56	6,55	35,6	2,25	3523	1761	1,94	11,2
LA10	P	20-ago	43	6,97	12,04	0,85	921	460	0,47	6,8;7,8
LA9	P	28-ago	28	7,02	49,8	4,03	531	265	0,28	9,8;11,1
LA55	P	04-set	27	7,15	19	1,72	344	172	0,18	19;20

#### 4. Table for sample storage

Composto	Tipo di contenitore	Conservazione	Tempo massimo di conservazione
Acidità e alcalinità	Polietilene, vetro	Refrigerazione*	24 ore
Andride carbonica	Polietilene, vetro		Analisi immediata
Azoto ammoniacale	Polietilene, vetro	Refrigerazione*	24 ore
Azoto nitrico	Polietilene, vetro	Refrigerazione*	48 ore
Azoto nitroso	Polietilene, vetro	Refrigerazione*	Analisi prima possibile
Azoto totale	Polietilene, vetro	Refrigerazione*	24 ore
Boro	Polietilene	Refrigerazione*	1 settimana
Calcio	Polietilene, vetro	Refrigerazione*	24 ore
Cianuri (totali)	Polietilene, vetro	Aggiunta di NaOH, fino a pH>12, refrigerazione al buio	24 ore
Cloro	Polietilene, vetro		Analisi immediata
Cloruro	Polietilene, vetro	Refrigerazione*	1 settimana
Conducibilità	Polietilene, vetro	Refrigerazione	Analisi immediata 24 ore
Durezza	Polietilene, vetro	Refrigerazione*	24 ore
Fluoro	Polietilene	Refrigerazione*	1 settimana
Fosfato inorganico	Polietilene, vetro	Refrigerazione*	24 ore
Fosforo totale	Polietilene, vetro	Aggiunta di H <sub>2</sub> SO <sub>4</sub> fino a pH<2 e refrigerazione	1 mese
Metalli disciolti	Polietilene, vetro	Filtrazione su filtri 0.45 micron, aggiunta di HNO <sub>3</sub> fino a pH<2	1 mese
Metalli totali**	Polietilene, vetro	Aggiunta di HNO <sub>3</sub> fino a pH<2	1 mese
Cromo (VI)	Polietilene, vetro	Refrigerazione*	24 ore
Mercurio	Polietilene, vetro	Aggiunta di HNO <sub>3</sub> fino a pH>2, refrigerazione	1 mese
Ossigeno disciolto (elettrodo)			Misura "in situ" analisi immediata
Ossigeno disciolto (metodo di Winkler)	Vetro	Aggiunta di reattivi di Winkler sul posto	24 ore
pH	Polietilene, vetro	Refrigerazione	Analisi immediata 6 ore
Potassio	Polietilene	Refrigerazione*	1 settimana
Silice	Polietilene	Refrigerazione*	1 settimana
Sodio	Polietilene	Refrigerazione*	1 settimana
Solfato	Polietilene, vetro	Refrigerazione*	1 mese
Solfito	Polietilene	Refrigerazione*	24 ore
Solfuro	Polietilene, vetro	Refrigerazione, aggiunta di acetato di zinco; aggiunta di NaOH fino a pH>9	1 settimana
Torbidità	Polietilene, vetro	Refrigerazione al buio	24 ore





Dal Degan thesis data (2000)

	Abano		Simione		Venezia		Villaverla		Caldeno		Sant'Ambrogio Valpolicella			Fumane			Alluvionale (Domoglia, Ospedaletto, San Pietro Incariano, Pescantina e Sant'Ambrogio di Valpolicella)										M29		M29 (Lazise)						
	A1	A2	S44	S45	V11	VILL1	CT12	SA50	SA51	SA52	SA53	F60	F61	3	5	6	8	10	11	14	16	22	23	24	25	26	M1	M2	M29	M29	M41	M42	M43		
Temperatura	65	40	65,0	63	67,3	75	26,6	12	12	13	14	14	31	28	43	29,2	46,4	30	40,3	19,3	40,3	19,3	18,9	19	27	19	36,2	41,2	24,00	23,50	30,00	24,50	23,40		
pH	7,33	7,45	6,76	6,92	7,45	8,34	7,46	7,5	7,7	7,3	7,7	7,5	7,5	7,49	7,44	7,7	7,71	7,34	7,5	7,1	6,9	7,2	7,25	7,2	7,25	7,2	7,6	7,42	8,08	8,11	7,96	7,7	7,5		
Conducibilita	4800	4900	4800	4880	4680	4653	4693	468	541	650	450	460	403	4070	730	1190	1338	953	1215	945	1020	785	952	952	952	430	1403	430	450	450	445	443	356		
Risultato test	2413	1405	2652	2676	517,1	264,1	448	337	380	458	432	310	260	170	527	892,5	590	653	714,75	675	690	734	565	565	565	276	950	320	370	320	319	256	319		
Durezza	1,6	0,3	1,58	1,51		0,05	0	0	0	0	0	0	0	0,0537	0	0,5	1,2	0	0,01	0,01	0,18	0,18	0	0	0	0	20,1	23,9	21,7	20,6	28	19	14		
NO3							8,2	15	15	20	24	8	8	9	1,51	2,2	0	13,49	0,18	0,18	0,18	0,18	0,18	0,18	0,18	0	0	0,12	0,06	0,02	0,16	0,06	0,12	0,022	
HCO3	180	178	329,508	341,712	250	116	262	279,38	267,18	323,3	336,72	281,82	223,3	269,488	341,6	294,02	209,8	395	223,36	484,34	436,76	484,34	436,76	384,76	485	461,16	314	195	278	291	187	325,74	326,96	237,9	
Calcio Ca	161	121	166,372	204,408	48	33	73	84	78	94	110	85,6	78	86	76,15	80	88	80	132	107	136	144	136	132	107	136	44	77	46	46	45	56	44	32	
Magnesio Mg	36	44	31,816	30,4	12	15	33	17	15,8	23,1	15,8	13,6	15,6	23,1	24,31	29	27	27	27	32	36	24	36,3	24	36,3	19	22	26	18	18	18	29	19	15	
Sodio Na	600	256	634,8	634,8	68	14,5	28	4,1	4,6	5,1	16,8	2,2	1,9	107	34,49	62,2	17,0	18,3	14,8	3,4	4,2	4,2	17,9	30,2	40	30	190	24,3	24,4	2,5	15,2	34,5	27,1	3,6	
Potassio K	22,8	22,8	66,47	70,38	28	6	5,5	1,7	1,3	1,2	1,8	0,8	0,8	13	5,47	7,9	18,3	7,1	7,1	32,6	2,2	2,4	2,4	2,4	2,4	2,4	2,4	2,4	2,4	2,4	2,5	2,8	2,7	3,6	
Cloruri Cl	1033	456	1163,098	1177,272	54,5	21	43	11	12	14	46	3	3	196	53,19	237,8	106	305	115,64	255	39	85	46	54,3	33	45	330	5	3,48	4,19	3	3	2		
Solfati SO4	389	316	240,15	211,332	55	38	106	29	26	28	28	7	10	100	62,43	137,5	64	94	114,2	90	54	58	44	48,6	43	4,1	112	0,4	0,4	0,7	9	1	13		
Arsenico																																			
SiO2	0,39	0,17	0,694	0,694		20	13								11,11	18	19,8	20,2	7,5								29	29	0,01	0,01	28,8	29,7	17,8		
Litio Li																																			
Fluoro F	3,5	2,6				0,64	0,6									0,5	1,1	1,1	0,19								0,2	1,3	0,25	0,18	0,26	0,15	0,19	0,22	
Bario Ba	0,11	0,06				0,06										0,061	0,089		0,06								0,34	0,15	0,09	0,11	0,16	0,19	0,096	0,13	
Stronzio Sr	3,5	2,6				1,02																						0,75	2,5	0,7	0,7				
Bromo Br	4,1	1,9	7,27	23,17											2,24																				
Ferro Fe	0,1	0,36				0,6	0	0	0	0	0	0	0	0	0	1	0,7	0,08	0,5	0	0	0	0	0	0	0	0,31	0,69	0,14	0,17	0,16	0	0,8		
Manganese Mn							0	0	0	0	0	0,01	0,0008			0,003	0,026		0,029	0,003							0	0,002	0,009	0	0,03	0,013	0,015	0,031	
Zinco Zn							0	0	0,0008																										
Cromo Cr							0	0	0,0015																										
Piombo Pb							0	0	0,0011																										
							0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,0044	0,0048	0,004	0	0	0	

DATA REGIONE VENETO

Data	ID	Nome	Località	T <sub>C</sub> aria	T <sub>C</sub> acqua	pH	Conduttività 25°C	NO <sub>3</sub> <sup>-</sup>	NO <sub>2</sub> <sup>-</sup>	Ammonio	PO <sub>4</sub> <sup>-3</sup>	Alc	ClO <sub>2</sub>	Na	Ca	Mg	K	Durezza Totale	As	Fe	Sr	Li	Mn	PROS					
18/11/2009	CF	Corno del Pado	Rovescano	13,5	49,4	7,85	1730	1035	0,11 <0,01	2	0,04	2	1,6	1,9	2	239	99,5	27,4	20,9	24,1	0,007 <0,002	<0,02	0,094	0,12	0,008	2,06	230		
03/02/2004	CF	Corno del Pado	Rovescano	6,3	51,1	7,2	1640	1024	0,25 <0,01	<1,0	1,4 <0,1	1,5	1,8	1,8	1,8	101	101	21,7	24,4 <0,005	0,004	0,49	0,12	0,12	<0,005	2,42	230			
18/04/2004	CF	Corno del Pado	Rovescano	13,5	59	7,2	1830	1047	0,87 <0,01	<1,0	1,9 <0,1	2,6	2,0	1,7	1,8	1,3	101	27,6	21,1	24,6	0,016	0,02	0,09	0,14	0,008	2,44	230		
13/07/2004	CF	Corno del Pado	Rovescano	17	49	7,1	1810	1056	0,25 <0,01	<1,0	1,6 <0,05	2,6	2,0	2	1,9	1,8	2	212,2	24,7	24,2	0,025	0,02	0,14	0,12	0,008	2,41	230		
01/03/1996	CA	Casale	Casa di Jarese	0,1	26,2	7,45	1436	914	0,15 <0,01	<1	1,6	0,04	2,5	1,6	0,7	192	79	26	16	24,4	0,012	0,02	0,16	0,11	0,04	2,5	198		
10/04/1996	CA	Casale	Casa di Jarese	13,7	39	7,42	1405	919	0,15 <0,01	<1	1,6	0,16	2,1	1,6	0,6	190	79	26	16	24,4	0,01 <0,002	0,4	0,08	0,11	<0,005	2,4	198		
15/06/1996	CA	Casale	Casa di Jarese	25,9	28,9	7,73	1328	866	0,19 <0,01	<1	1,3	0,07	2,3	1,3	0,8	184	77	24	16	18,1	0,025 <0,002	0,49	0,16	0,1	0,01	2,4	198		
09/11/1996	CA	Casale	Casa di Jarese	24	28,5	7,26	1346	878	0,14 <0,01	<1	1,6	0,05	2,3	1,6	0,8	197	75	25	17	19	0,012	0,02	0,48	0,13	0,02	1,9	198		
18/05/1996	SC	Bevagna	Casa di Jarese	18,2	29,8	7,41	1374	929	0,14 <0,01	<1	1,7	0,45	2,3	1,6	<1	190	76	26	16	24,7	0,1	0,02	0,12	0,1	0,04	2,17	204		
06/09/1996	SC	Bevagna	Casa di Jarese	18,9	40,2	7,4	1441	947	0,18 <0,01	<1	1,6	0,04	2,3	1,6	<1	187	77	27	16	24,4	0,13	0,02	0,2	0,11	0,04	2,56	204		
18/11/1996	SC	Bevagna	Casa di Jarese	11,3	40,1	7,38	1410	950	0,15 <0,01	<1	1,7	0,06	2,1	1,6	<1	195	76	26	16	24,7 <0,01	0,02	0,14	0,09	0,21	0,02	2,54	204		
12/11/2007	VQ	Villa Quaranta	Corchiesano	12,2	21,2	7,4	921	641 <0,02	0,01	0,8	0,02	4,0	244 <0,1	0,2	1	0,1	96,1	76,7	24,4	11	20	0,005	0,024	0,02	0,1	<0,005	1,24	792	
16/05/2007	VQ	Villa Quaranta	Corchiesano	20,6	21,4	7,4	1011	685 <0,02	<0,01	0,9	0,01	4,1	250 <0,1	1,1	1	0,3	112	80,8	24,4	11,4	21,2	0,006 <0,002	0,02	0,06	0,11	<0,005	1,35	792	
11/07/2007	VQ	Villa Quaranta	Corchiesano	25,8	22	7,4	924	637 <0,02	<0,01	0,9	<0,01	4,1	250 <0,1	0,9	0,3	0,1	91,2	80,4	24,8	11,1	21,3	0,01	0,02	0,07	0,02	0,11	<0,005	1,6	792
20/01/2007	VQ	Villa Quaranta	Corchiesano	10	21,4	7,4	991	692 <0,02	0,01	0,1	<0,01	2,8	221 <0,1	0,9	0,1	10,4	80,2	24,5	11,9	21,1	0,018 <0,002	0,13	0,06	0,11	<0,005	1,58	792		
18/07/2004	AB3	Alcova Basso	San Giuliano	25	22	7,9	481	312 <0,04	<0,01	6	<0,01	230 <0,02	0,11 <0,02	0,6	10	61,3	37,7	2,2	27	0,028 <0,001	0,2	0,16	0,026	0,033	0,027	1,7			
18/07/2004	AB1	Alcova Basso	San Giuliano	25	22	7,9	495	320 <0,04	<0,01	<0,1	<0,01	231 <0,02	0,11 <0,02	0,5	11	51,3	34,6	2,6	24,5	0,029 <0,001	0,2	0,06	0,026	0,027	0,025	1,7			
14/09/2008	GB3	Osana	Passarona	18,2	42,5	7,1	1197	779 <0,03	0,02 <1	0,1	1,4 <0,02	37	319 <0,1	1,34	1,2	0,1	148,1	80,6	32,7	14,9	33,5	0,011	0,02	0,12	0,02	1,62	371		
14/01/2004	GB1	Osana	Passarona	11	45,6	7,4	1370	826	0,21 <0,01	1,1	1,4	0,02	37	318 <0,1	1,3	1,4	0,6	176	88,8	24,4	14	21,1	0,017	0,02	0,15	0,02	1,62	371	
03/03/2004	GB1	Osana	Passarona	6,0	45,7	7,4	1306	837 <0,03	<1	1,9	0,01	25	314 <0,1	1,3	1,4	0,8	178	89,4	24,6	15,5	21,1	0,017	0,02	0,15	0,02	1,68	371		
19/04/2004	GB1	Osana	Passarona	14	45,5	7,4	1313	840	0,07 <0,01	<1	1,8	0,01	27	316 <0,1	1,7	1,4	0,8	171	89,6	24,5	15,1	21,1 <0,005	0,02	0,15	0,02	1,68	371		
11/07/2004	GB1	Osana	Passarona	19	39	7,3	1327	861	0,06 <0,01	<1	1,6	0,07	27	318 <0,1	1,5	1,4	0,8	168,4	89,1	24,6	15	21,2	0,028	0,025	0,12	0,16	1,68	371	

6. Table sampling of water for Sr and S isotopic analysis

CNR - ISTITUTO DI GEOSCIENZE E GEORISORSE LABORATORI DI CHIMICA ISOTOPICA E SPETTROMETRIA DI MASSA							
Data		Sigla	$^{87}\text{Sr}/^{86}\text{Sr}$	Err $2\sigma$ (95% c.l.)	MSWD	Probabilità	Archivio
14:10:15		<b>Brentella (LA7)</b>	0,707999	0,000014	0,342	1,00	697.dat
15:10:15		<b>LA 9</b>	0,708136	0,000012	0,471	1,00	698.dat
16:10:15		<b>Fontanon (LA13)</b>	0,707835	0,000018	0,558	1,00	699.dat
17:10:15		<b>LA 10</b>	0,708506	0,000016	0,495	1,00	700.dat
19:10:15		<b>LA 23</b>	0,708614	0,000024	0,480	1,00	701.dat
20:10:15		<b>LA 46</b>	0,708641	0,000011	0,380	1,00	702.dat
		<b><math>^{87}\text{Sr}/^{86}\text{Sr}</math> normalizzato al valore di <math>^{86}\text{Sr}/^{88}\text{Sr}</math> di Nier (1938)</b>					

Dott. Giancarlo Cavazzini