Geologic Italian Adventure Consortium Field Guide 2005

GIAC Seminar Class
Paul Gettings, Matt Affolter, Stephanie Bear,
Aaron DeNosaquo, Abraham Emond, Payton Gardner,
Nancy Harris, Sonja Heuscher, Greg Nielsen,
Joe Sertich, and Katrina Settles

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Chapter 1

Introduction

1.1 GIAC: Geologic Italian Adventure Consortium

> *"To learn geology one must travel widely and observe carefully, for geology is learned through the soles of your shoes, not the seat of your pants!"* -Walter L. Manger

A group of 11 Department of Geology and Geophysics graduate students, otherwise known as Geologic Italian Adventure Consortium (GIAC), formed a student-run seminar on the geology and geophysics of unique Italian terrains in Spring 2005. The seminar culminated in a three-week field trip to Italy in June 2005. The trip focused on unique geology available in Italy, with emphasis on: historic volcanism and it's related hazards at Vesuvius and Pompeii, structural geology of a continent-continent collision zone in the Alps and Apennines, and aspects of engineering geology to mitigate hazards in Venice. The trip promoted field-based learning of a unique geologic and cultural locality, and provided a unique experience for us to travel to a different part of the world.

1.1.1 On the purpose of GIAC

While we, as students, spend a lot of time learning in classrooms and labs, the essence of being a geologist is getting out to see the land that we study. As graduate students, we are in the process of building the foundation on which our contributions to science will stand. We are focused on making the transition from undergraduate "consumers of science" to graduate "producers of science." Being able to experience the diverse, and unique, geologic settings of Italy helps us along the path.

GIAC continues a tradition among enthusiastic incoming graduate students in the Department of Geology and Geophysics of developing a student-run seminar concentrating on an unfamiliar, but geologically significant, region of this planet. The entering class of 1999 traveled to New Zealand, and the class of 2002 travelled to Kenya to experience the East African Rift Valley. We chose Italy for this trip because of the diverse geolgic settings and the relative ease of travel.

1.1.2 On group size

To create an active and informed learning environment, both in the classroom and on a field trip, we need a sizable group of students. As the field trip is student led, learning and logistics work best if each student can become an expert on a field stop (or two). This allows our collected knowledge, covering the full range of geology and geophysics, to be passed between all of us and our faculty advisors, Dr. David Chapman (in Utah), and Dr. Fulvio Tonon (in Italy).

1.1.3 GIAC benefits to the University

A student-led, community- and University-supported international geologic expedition will contribute to the reputation and recruiting of our University, our College, and our Department. While on the field trip, the seminar students will promote the reputation of the University to the broader world outside Utah. The success of this trip, which is solely dependent on funding, will provide a valuable recruiting tool for prospective graduate students. Since graduate students form an integral part of the Department in teaching and research roles, better recruitment of graduate students also benefits undergraduates in the Department.

1.2 Student Emergency Contact Information

Student	Emergency Contact	Number
Matt Affolter	Dale Affolter	818-822-1101
Stephanie Bear	Donna/Woody Bear	614-352-6728
Aaron DeNosaquo	Sam DeNosaquo	847-256-2250
Abraham Emond	Chris Emond	508-224-2138
Payton Gardner	Lindsey Gardner	801-597-4974
Paul Gettings	Mark Gettings	520-797-1572
Nancy Harris	Barbara Hamilton	920-746-8893
Sonja Heuscher	Enno Heuscher	970-241-1370
Greg Nielsen	Brenda Nielsen	801-737-4658
Joe Sertich	Dana Bastian	303-694-2364
Katrina Settles	Joel/Sarah Settles	763-479-3529

1.3 Trip Itinerary

1.3.1 Calendar

Sun	Mon	Tue	Wed	Thu	Fri	Sat
22 May	**23**	**24** Depart SLC for Rome	**25** Arrive Rome; train to Naples *Naples*	**26** Vesuvius *Naples*	**27** Hercul./ Villa Regina/ Arch. Museum *Naples*	**28** Pompeii *Naples*
29 Transit to Florence area *Volterra*	**30** Appenn./ Siena/ Larderello *Volterra*	**31** Appenn./ Cinque Terra *Massa*	**1 June** Appenn./ Val Graveglia *Massa*	**2** Appenn./ Alpi Apuane *Massa*	**3** Appenn./ Free day *Florence*	**4** Transit to Venice/ Free day *Florence*
5 Free day *Venice*	**6** Consort. *Venice*	**7** Explore Venice *Venice*	**8** Vajont Landslide *Passo di Fulzarego*	**9** Sella *Selva*	**10** Alps transit *Aprica*	**11** Ivrea-Verbano *Verbania*
12 Ivrea-Verbano Zone *Verbania*	**13** Transit to Milan *Milan*	**14** End of trip; depart Milan for SLC	**15**	**16**	**17**	**18**

Locations in italics are lodging for that night; see next section for details (telephone #, etc.) for each town. Not all students will return to SLC on 14 June.

1.3.2 Lodging Details

Naples

Hotel Zara
Via Firenze 81
Tel: 39-081-287-125

Volterra

Seminario Vescovile di Sant'Andrea
Tel: 0588-860-281
Viale Vittori Veneto 2

Massa

Hotel Daisy
Tel: 0585-240-108
Via Verona, 12

Florence

Autopark
Tel: 055-431-771
Val de Gola 1

Venice

Bax Pax Venice
Tel: 39-3479-982-676
Camp Santa Margherita 2931

Passo Di Fulzarego

Albergo La Baita [in Andraz]
Tel: 39-0436-7172
32020 Livinallongo del Col di Lana

Selva

Hotel Sun Valley
Fam. Nogler Via Dantercepies N-7
Tel: 0471-795152
39048 Selva Val Gardena

Aprica

Hotel Roma
Tel: 39-0342-748-993
Corso Roma 159, Sondrio

Verbania

Ostello Verbania
Tel: 0323-501-648
Via alle Rose 7, Verbania

Milan

Hotel del Sole
Tel: 0229-512-971
Via Gaspare Spontini 6, Milan

1.4 A Brief Tectonic History of Italy

The following is drawn from the lecture by Prof. John M. Bartley on April 14, 2005. The lecture was a summary of *Rosenbaum et al.* (2002).

For this discussion, we start with the plate configuration of the Triassic: Africa is still part of Gondwana, and sutured to the Americas from the late Paleozoic Hercynian orogeny; Eurasia is also sutured to the Americas, with most of the southern European continent within the Hercynian orogen; Adria (also called Apulia), which is the future Italy, is a continental mass in the Tethyan ocean, and may be a northern promontory on Africa/Gondwana. As of the late Triassic, but before the breakup of Pangea, the forelands of Africa, Eurasia, and Adria are covered with shallow-marine carbonate-bank sediments.

With the breakup of Pangea, the Tethyan ocean began to close, colliding Africa and Adria into Eurasia: as the Atlantic opens Eurasia is subducted to the south under the northern edge of Adria and Africa. This is the western edge of a continuous convergent plate-boundary system extending from Eurasia to present-day Indonesia/Papua-New Guinea; in the Mediterranean region, the Africa/Eurasia collision is known as the Alpine orogen. The majority of this orogeny took place in the late Eocene to middle Miocene (40-15 Ma), but events extend from the late Cretaceous to the late Cenozoic. Moreover, due to the complex geometries at a continent-continent boundary, events along the margin are very diachronous; correlated events along the margin are not necessarily contemporaneous!

The Alpine orogen continued until continental Eurasian crust reached the Adrian margin, which stopped subduction. Subduction resumed to the south of Adria, but with reversed sense: seafloor was now subducted to the north, under Eurasia.

The modern Mediterranean region is dominated by these more recent tectonics, mostly extensional, that occured after the end of the Adria-Eurasia collision. In particular, the continuing subduction of Miocene ocean floor under Eurasia, with a slow Africa-Eurasia convergence rate, causes subduction rollback, which extends the Eurasian/Adrian plate. A cartoon depiction of subduction rollback is shown in figure 1.1. Subduction rollback extension

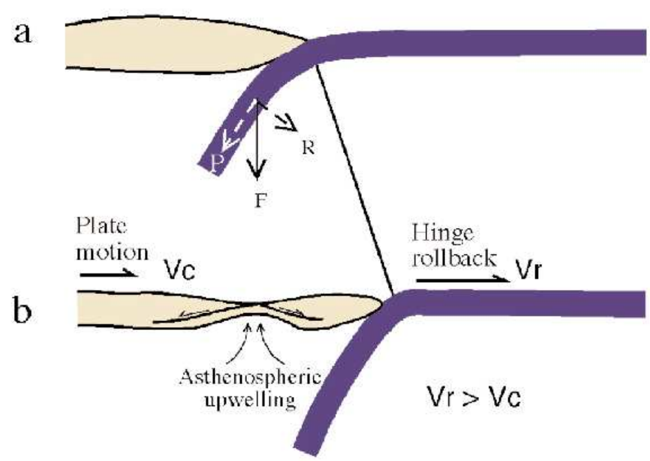


Figure 1.1: Cartoon of subduction rollback. (a) Subduction zone without rollback. (b) Subduction zone with rollback. Rollback occurs when the absolute plate motion of the overriding plate is less than the convergence rate at the subduction zone. From *Rosenbaum et al.* (2002), figure 3.

forms a back-arc basin in the Eurasian plate, similar to the Sea of Japan. Some extension in the region may have been due to gravitational collapse of upthrust rock when the convergence rate of Africa and Eurasia slowed, but this is not likely the predominant extensional mechanism.

The extension due to subduction rollback has been accommodated in the Mediterranean basins in two ways: (1) by stretching of the lithosphere, and (2) by rupturing of the lithosphere and seafloor spreading. Stretching is currently happening in the eastern Mediterranean, and both stretching and seafloor spreading have occurred in the western Mediterranean. With either method of accommodation, the rollback extension explains thrust faulting at the edge of the continental mass (due to subduction) next to highly stretched/ruptured lithosphere (due to extension). Rollback extension also provides an explanation for the the small landmasses pulled south from the Eurasian margin into the Mediterranean, and thrust up onto Africa (forming the Maghrebides) and Adria (forming the Appennines).

Chapter 2

Reference Maps

Figure 2.1: Political regions of Italy.

Figure 2.2: Northern Italy, from Times Atlas of the World.

Figure 2.3: Southern Italy, from Times Atlas of the World.

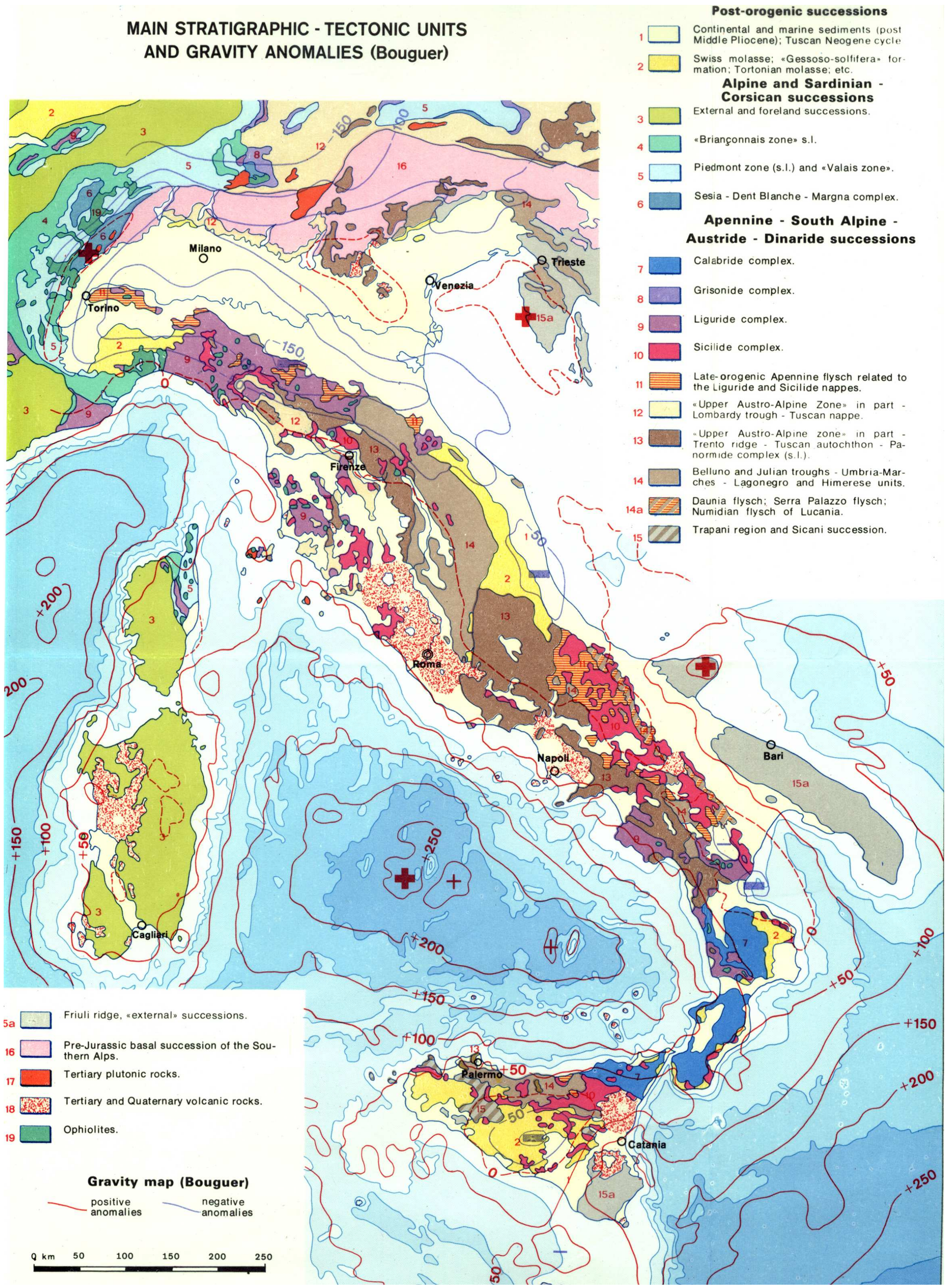


Figure 2.4: Tectonic map of Italy, with Bouguer gravity anomalies.

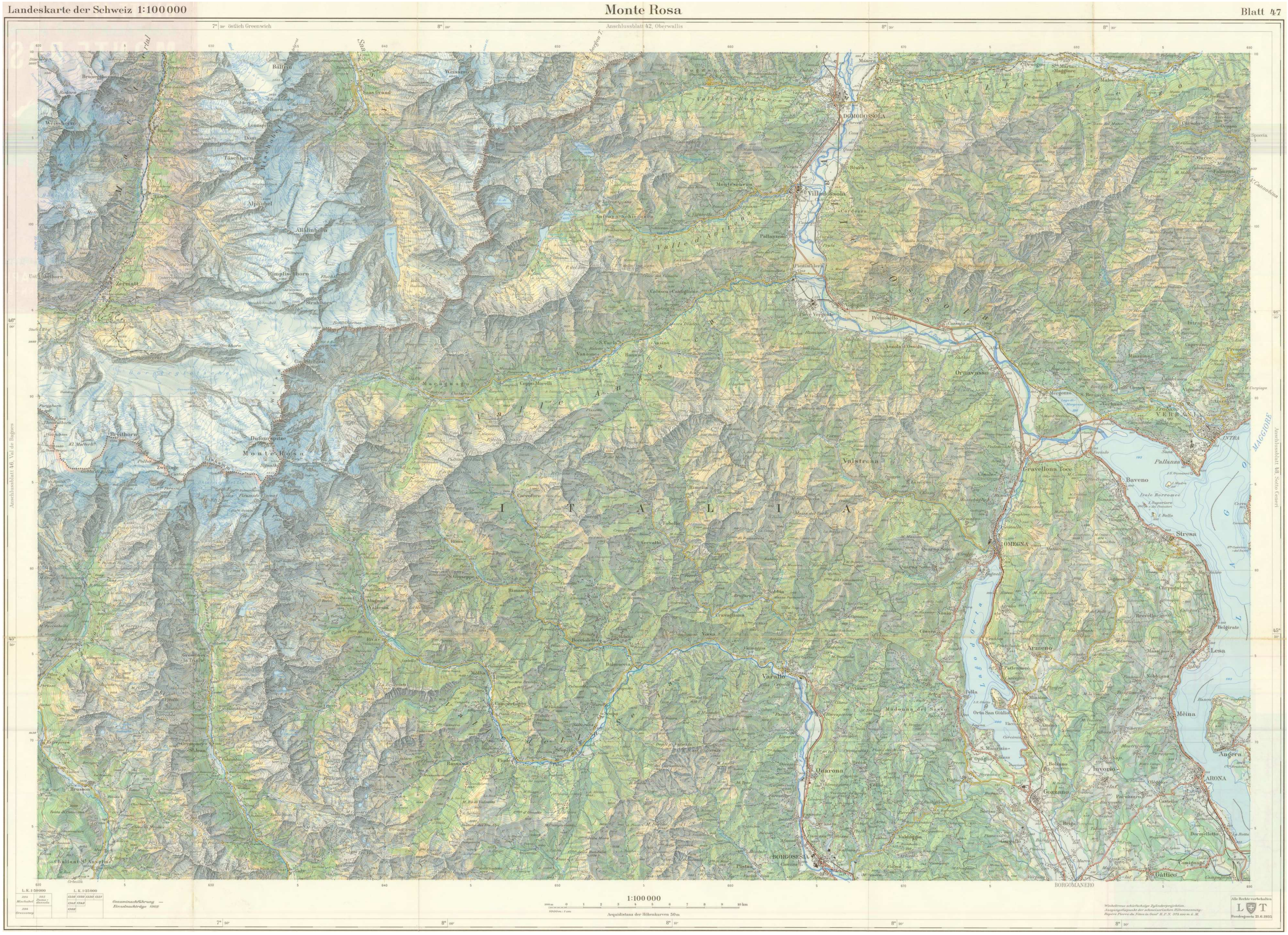


Figure 2.5: Monte Rosa topographic map, at 1:100 000 scale.

Figure 2.6: Portion of geologic map of northwestern Italy and Switzerland. Scale is 1:500 000. See following figures for legend.

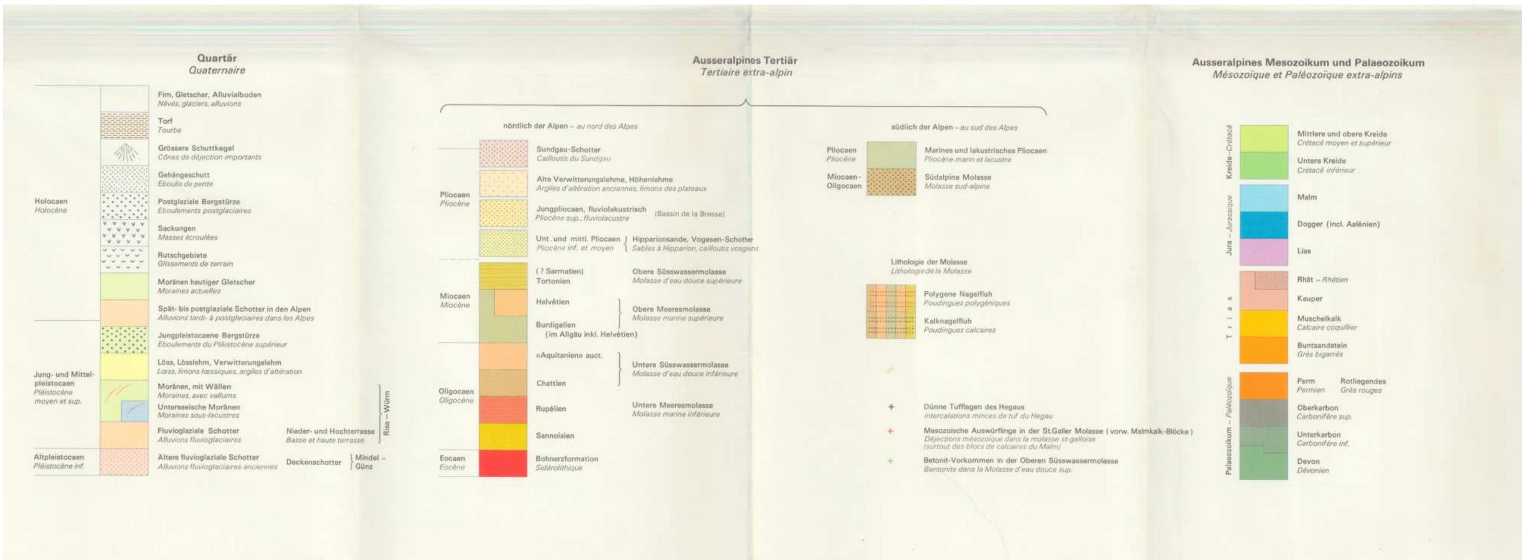


Figure 2.7: Page 1 of 3 of legend for figure 2.6.

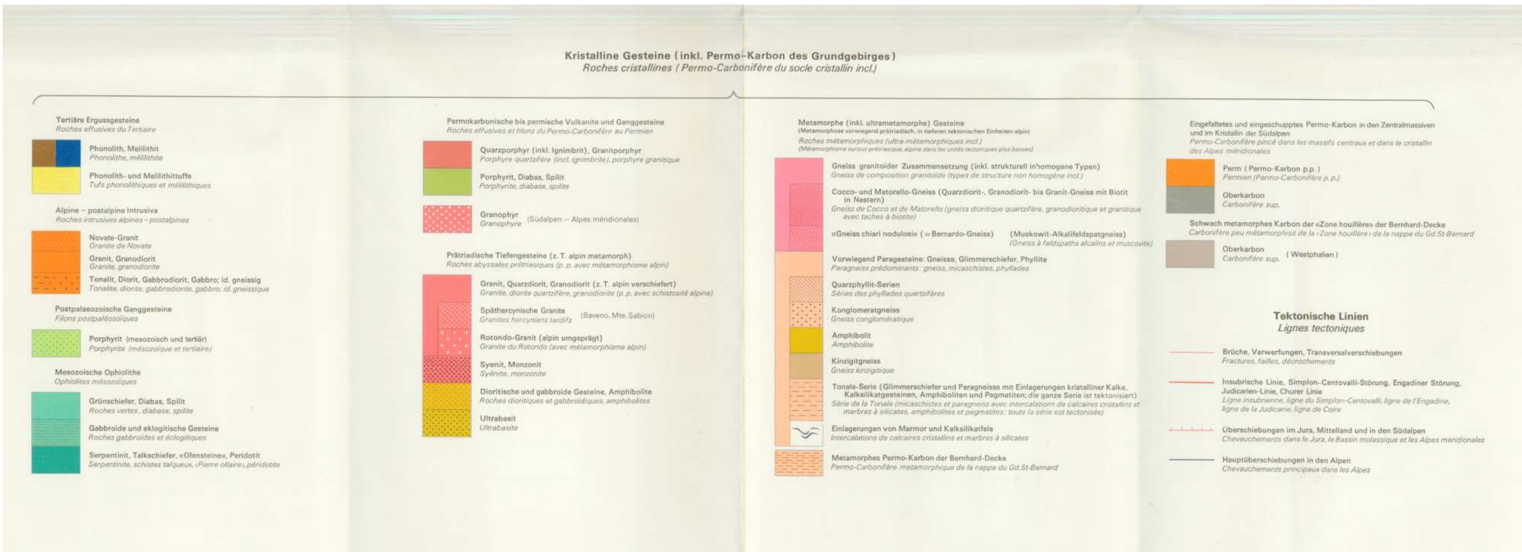


Figure 2.8: Page 2 of 3 of legend for figure 2.6.

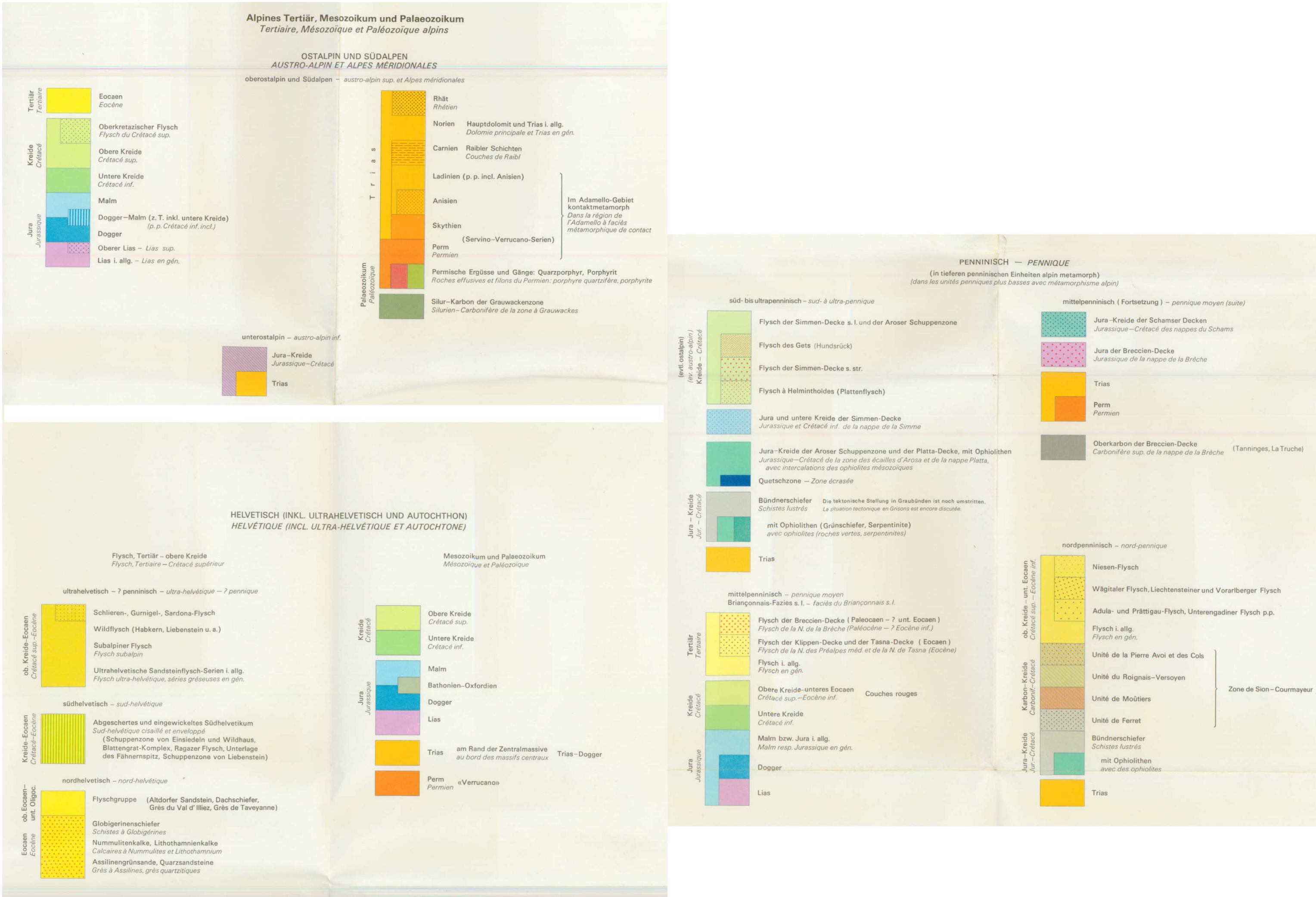


Figure 2.9: Page 3 of 3 of legend for figure 2.6.

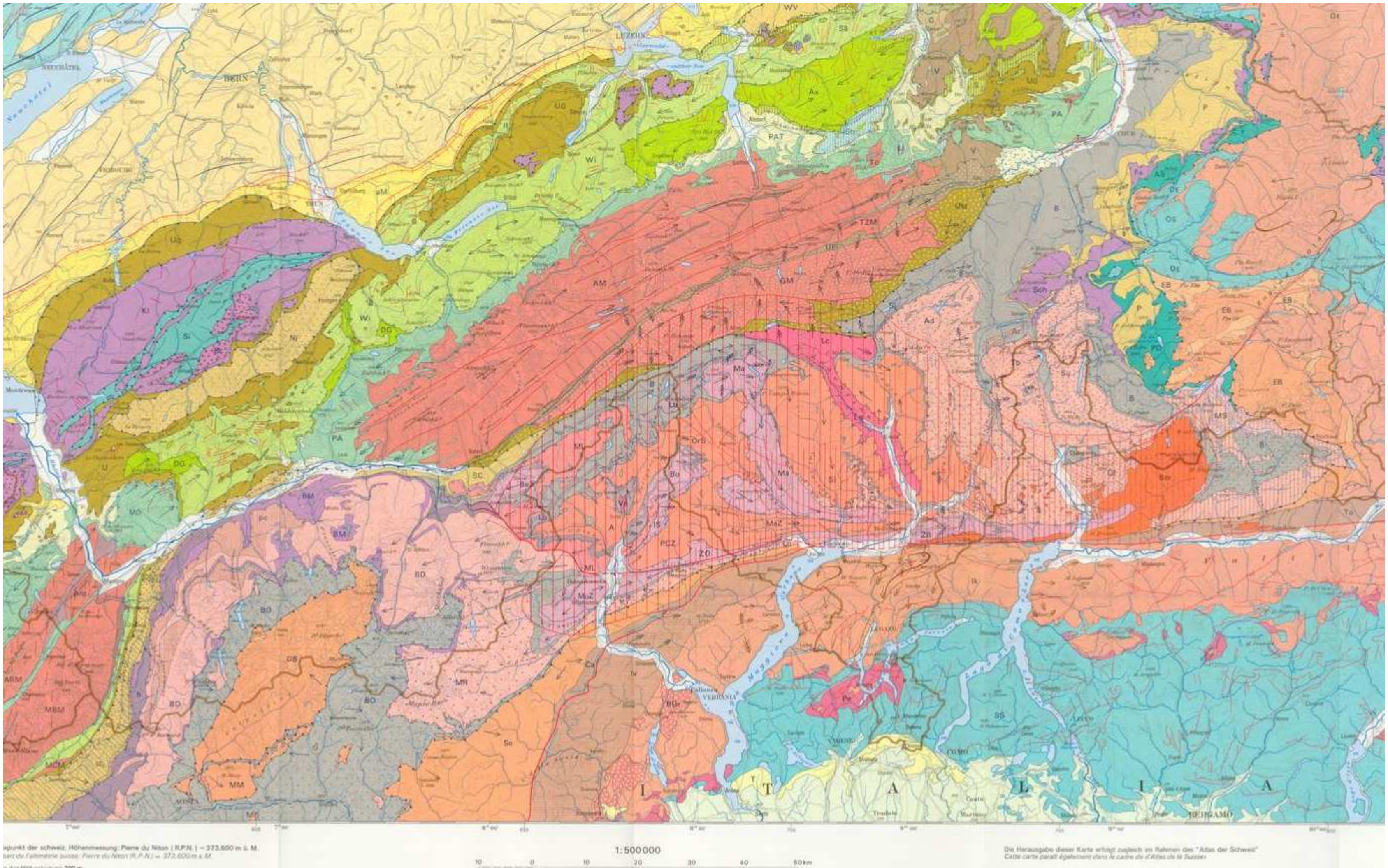


Figure 2.10: Portion of a tectonic map of northwestern Italy. Scale is 1:500 000. Reproduced from Swiss Geologic Commission map. See next figure for legend.

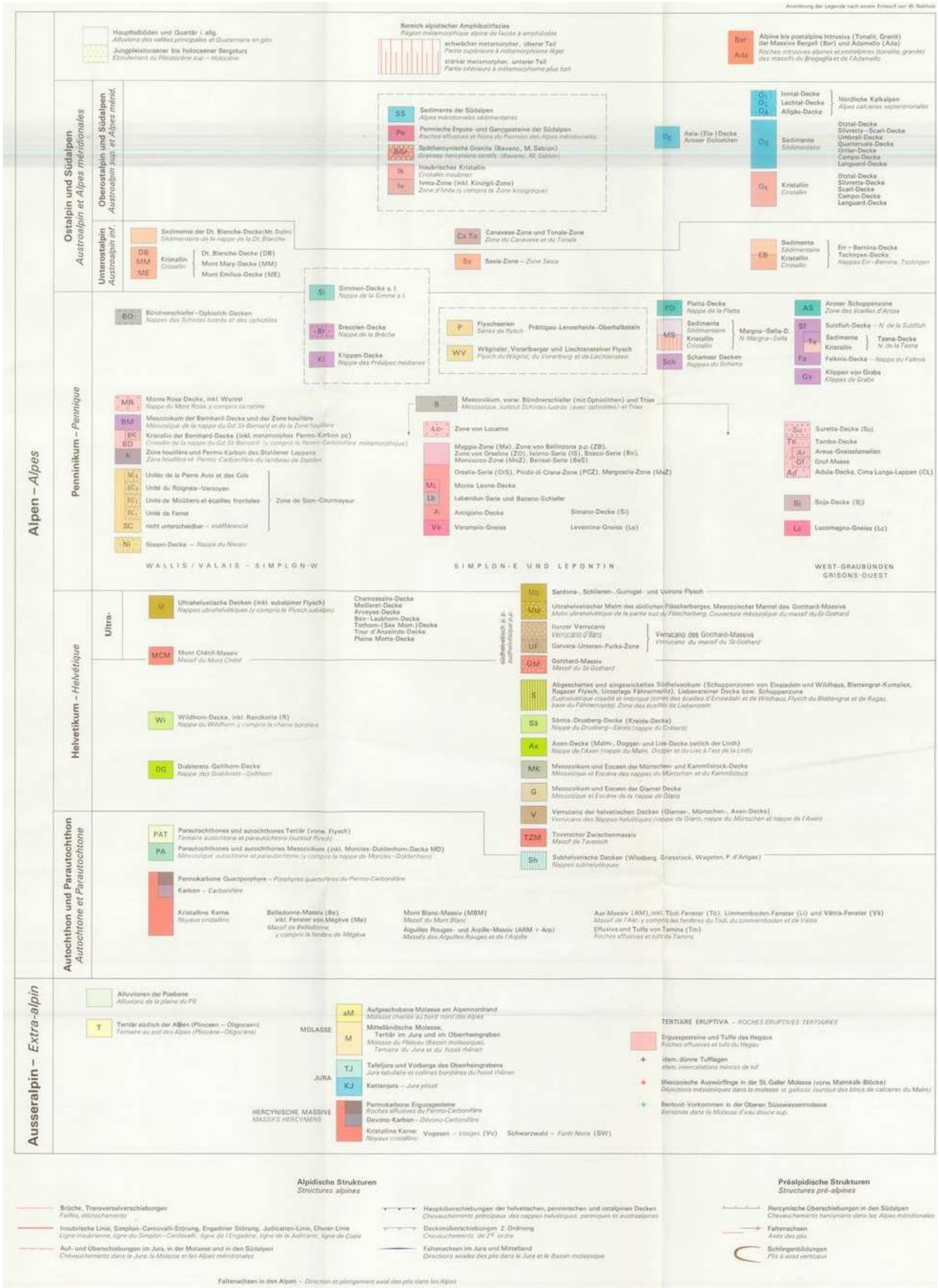


Figure 2.11: Legend for tectonic map of NW Italy (figure 2.10).

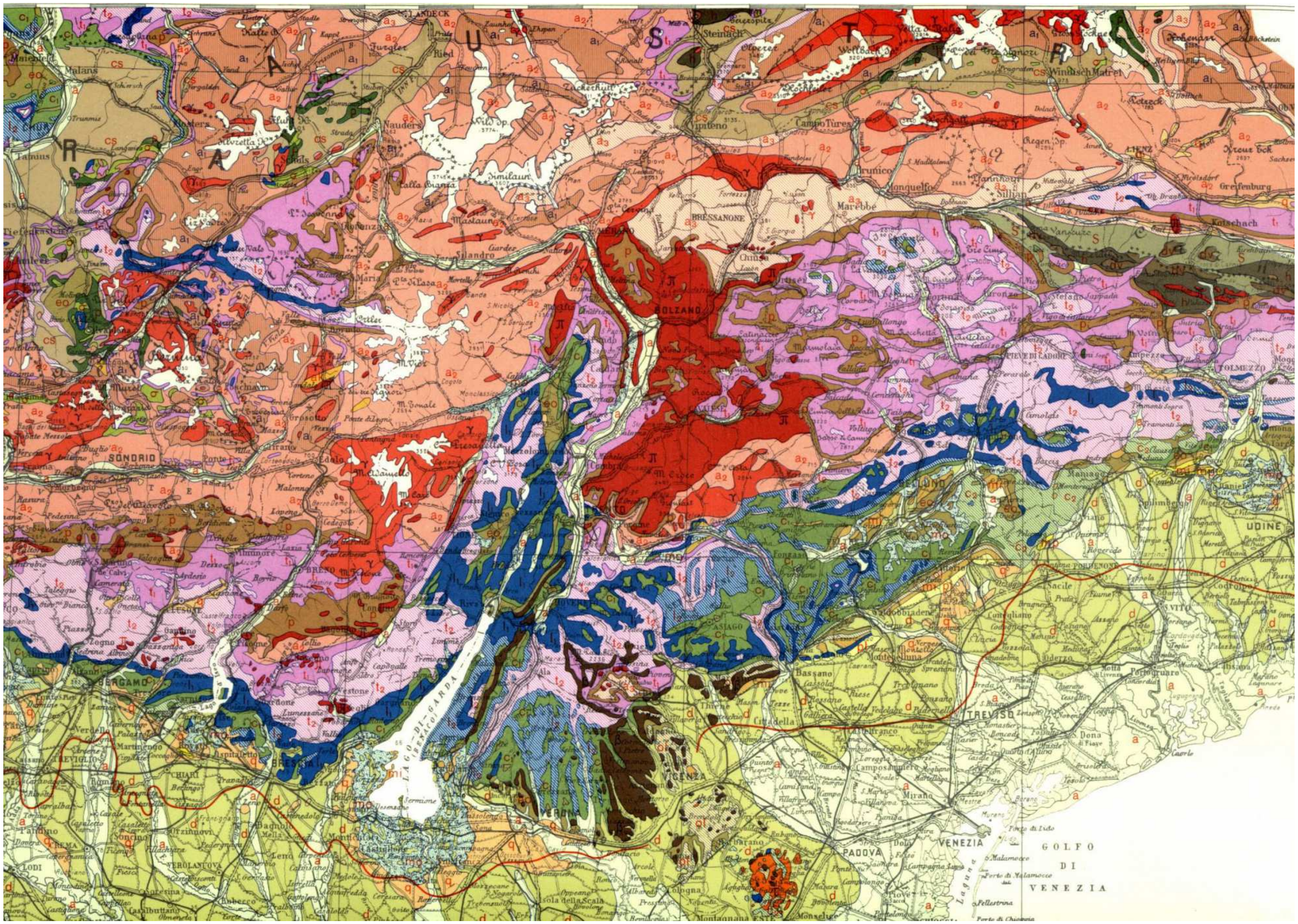


Figure 2.12: Geology of the Dolomites, Italian Alps. See next figure for key to geology.

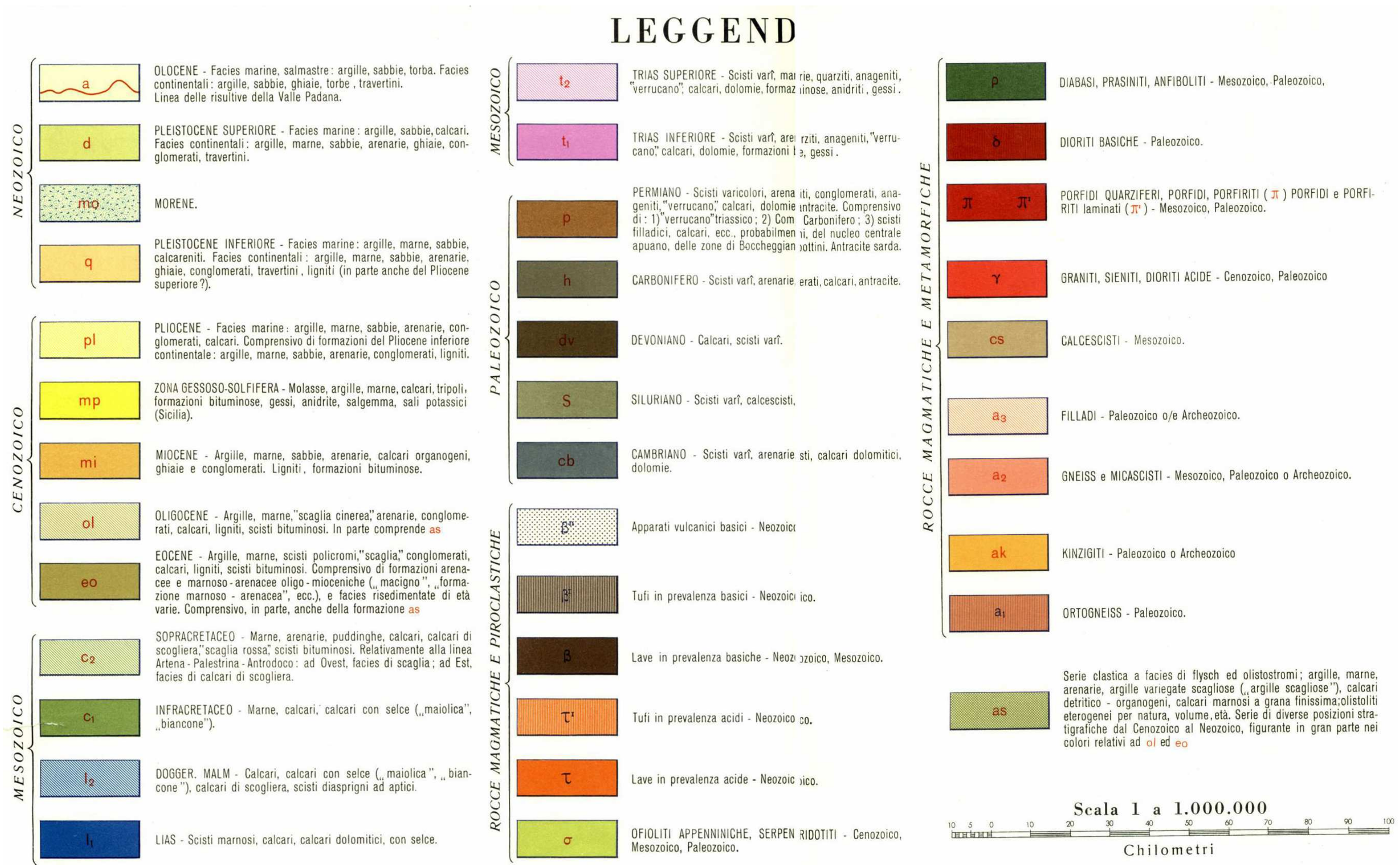


Figure 2.13: Legend for Dolomites geology (figure 2.12).

Chapter 3

Volcanics

3.1 Vesuvius

3.1.1 Introduction

"Vesuvio (Vesuvius) is probably the most famous volcano on Earth, and certainly one of the most, if not the most dangerous" (*Bencke*, accessed 2005). Its reputation derives not just from its geologic history but also from the way "its history is intimately interwoven with the history of humanity" (*Bencke*, accessed 2005). Although Vesuvius is best known for its massive eruption in AD 79 (burying Pompeii and other nearby villages), the volcano remains an active threat to nearby communities. Approximately one million people currently live within the danger zone (*Highton*, accessed 2005). The last eruption occurred in 1944 and the volcano is now generally considered to be in a repose stage. It is unknown how long this period will last; based upon past behavior the volcano could remain in repose for many centuries. In general, the longer the volcano remains inactive the larger the ensuing eruption is likely to be. Thus, the volcano may be building toward the largest eruption since 1631 (*Anonymous*, accessed 2005a).

A map of Vesuvius and its' surroundings is shown in figure 3.1.

3.1.2 Common Volcanic Terms

[From *Anonymous* (accessed 2005b).]

Ejecta Types

- Ash: Fine particles of pulverized rock with diameters <2 mm blown from an explosion vent. Ash may be either solid or molten when first erupted. By far the most common variety is vitric ash – glassy particles formed by gas bubbles bursting through liquid magma.

Figure 3.1: Map of Vesuvius and surroundings.

- Block: Angular chunk of solid rock >24 mm in diameter which is ejected during an eruption.
- Bomb: Fragment of molten or semi-molten rock >64 mm in diameter which is blown from an eruption. Because of their plastic condition, bombs are often modified in shape during their flight or upon impact.
- Lapilli: Literally, "little stones." Round to angular rock fragments 2–64 mm in diameter which may be ejected in either a solid or molten state.
- Tephra: A general term for materials of all types and sizes that are erupted from a crater or volcanic vent and deposited from the air.

Rock/Deposit Types

- 'A'a: Hawaiian word used to describe a lava flow whose surface is broken into rough angular fragments.
- Agglutinate: A pyroclastic deposit consisting of an accumulation of originally plastic ejecta and formed by the coherence of the fragments upon solidification.
- Andesite: Volcanic rock (or lava) characteristically medium dark in color and containing 54–62% silica and moderate amounts of iron and magnesium.
- Basalt: Volcanic rock (or lava) that characteristically is dark in color, contains 45–54% silica, and generally is rich in iron and magnesium.
- Dacite: Volcanic rock (or lava) that characteristically is light in color and contains 62–69% silica and moderate a mounts of sodium and potassium.
- Hyaloclastite: A deposit formed by the flowing or intrusion of lava or magma into water, ice, or water-saturated sediment and its consequent granulation or shattering into small angular fragments.
- Ignimbrite: The rock formed by the widespread deposition and consolidation of ash flows and Nuees Ardentes. The term was originally applied only to densely welded deposits but now includes non-welded deposits.
- Obsidian: A black or dark-colored volcanic glass, usually composed of rhyolite.
- Pahoehoe: A Hawaiian term for lava with a smooth, billowy, or ropy surface.

- Pumice: Light-colored, frothy volcanic rock, usually of dacite or rhyolite composition, formed by the expansion of gas in erupting lava. Commonly seen as lumps or fragments of pea-size and larger, but can also occur abundantly as ash-sized particles.

- Rhyolite: Volcanic rock (or lava) that characteristically is light in color, contains 69% silica or more, and is rich in potassium and sodium.

- Scoria: A bomb-size (>64 mm) pyroclast that is irregular in form and generally very vesicular. It is usually heavier, darker, and more crystalline than pumice.

- Trachyte: A group of fine-grained, generally porphyritic, extrusive igneous rocks having alkali feldspar and minor mafic minerals as the main components, and possibly a small amount of sodic plagioclase.

- Tuff: A general term for a rock formed of pyroclastic material.

Other Terms

- Active Volcano: A volcano that is erupting. Also, a volcano that is not presently erupting, but that has erupted within historical time and is considered likely to do so in the future.

- Ash Flow: A turbulent mixture of gas and rock fragments, most of which are ash-sized particles, ejected violently from a crater or fissure. The mass of pyroclastics is normally of very high temperature and moves rapidly down the slopes or even along a level surface.

- Ashfall (Airfall): Volcanic ash that has fallen through the air from an eruption cloud. A deposit so formed is usually well sorted and layered.

- Caldera: The Spanish word for cauldron, a basin-shaped volcanic depression; by definition, at least a mile in diameter. Such large depressions are typically formed by the subsidence of volcanoes. Crater Lake occupies the best-known caldera in the Cascades.

- Cinder Cone: A volcanic cone built entirely of loose fragmented material (pyroclastics.)

- Composite Volcano: A steep volcanic cone built by both lava flows and pyroclastic eruptions.

- Compound Volcano: A volcano that consists of a complex of two or more vents, or a volcano that has an associated volcanic dome, either in its crater or on its flanks. Examples are Vesuvius and Mont Pelee.

- Conduit: A passage followed by magma in a volcano.
- Crater: A steep-sided, usually circular depression formed by either explosion or collapse at a volcanic vent.
- Debris Flow: A mixture of water-saturated rock debris that flows downslope under the force of gravity (also called lahar or mudflow).
- Dome: A steep-sided mass of viscous (doughy) lava extruded from a volcanic vent (often circular in plane view) and spiny, rounded, or flat on top. Its surface is often rough and blocky as a result of fragmentation of the cooler, outer crust during growth of the dome.
- Dormant Volcano: Literally, "sleeping." The term is used to describe a volcano which is presently inactive but which may erupt again.
- Extinct Volcano: A volcano that is not presently erupting and is not likely to do so for a very long time in the future.
- Fissures: Elongated fractures or cracks on the slopes of a volcano. Fissure eruptions typically produce liquid flows, but pyroclastics may also be ejected.
- Flank Eruption: An eruption from the side of a volcano (in contrast to a summit eruption.)
- Fumarole: A vent or opening through which issue steam, hydrogen sulfide, or other gases. The craters of many dormant volcanoes contain active fumaroles.
- Lahar: A torrential flow of water-saturated volcanic debris down the slope of a volcano in response to gravity. A type of mudflow.
- Lava: Magma which has reached the surface through a volcanic eruption. The term is most commonly applied to streams of liquid rock that flow from a crater or fissure. It also refers to cooled and solidified rock.
- Lava Dome: Mass of lava, created by many individual flows, that has built a dome-shaped pile of lava.
- Lava Fountain: A rhythmic vertical fountainlike eruption of lava.
- Lava Lake (Pond): A lake of molten lava, usually basaltic, contained in a vent, crater, or broad depression of a shield volcano.
- Lava Tube: A tunnel formed when the surface of a lava flow cools and solidifies while the still-molten interior flows through and drains away.

- Magma: Molten rock beneath the surface of the earth.
- Nuees Ardentes: A French term applied to a highly heated mass of gas-charged ash which is expelled with explosive force and moves hurricane speed down the mountainside.
- Phreatic Eruption (Explosion): An explosive volcanic eruption caused when water and heated volcanic rocks interact to produce a violent expulsion of steam and pulverized rocks. Magma is not involved.
- Plug: Solidified lava that fills the conduit of a volcano. It is usually more resistant to erosion than the material making up the surrounding cone, and may remain standing as a solitary pinnacle when the rest of the original structure has eroded away.
- Plug Dome: The steep-sided, rounded mound formed when viscous lava wells up into a crater and is too stiff to flow away. It piles up as a dome-shaped mass, often completely filling the vent from which it emerged.
- Spatter Cone: A low, steep-sided cone of spatter built up on a fissure or vent. It is usually of basaltic material.
- Stratovolcano: A volcano composed of both lava flows and pyroclastic material.
- Surge: A ring-shaped cloud of gas and suspended solid debris that moves radially outward at high velocity as a density flow from the base of a vertical eruption column accompanying a volcanic eruption or crater formation.
- Vent: The opening at the earth's surface through which volcanic materials issue forth.
- Vesicle: A small air pocket or cavity formed in volcanic rock during solidification.
- Vulcan: Roman god of fire and the forge after whom volcanoes are named.

3.1.3 Volcanic Eruption Types

One common system for classifying volcanic eruptions is based upon the relative "explosiveness" of eruptions. Categories in this system are named for specific volcanoes that exhibit characteristic eruptive patterns. Below is a list of eruption types in order of increasing energy. Volcanic activity on Vesuvius has ranged from Hawaiian style eruptions to Plinian events.

[From *Anonymous* (accessed 2005b).]

- Hawaiian eruptions: Characterized by quiet, effusive eruptions that result from low viscosity, low gas content, and high eruption temperature. Hydrostatic pressure (from lava higher in the system) can produce spectacular lava fountains. Lava accumulates near the vent to produce cinder cones. Lava flows are thin, fluid, and extensive. Flow types can be pahoehoe or 'a'a. Repeated eruptions form gently sloping mounds of lava called "shield volcanoes." Named after the volcanoes in the U.S. Hawaiian Islands.

- Flood Eruptions: Similar in character to Hawaiian eruptions but on a much larger scale. Very large volumes of lava are extruded (usually from fissures) forming thick accumulations of laterally extensive basalt (or less commonly rhyollite). Examples include the Columbia River and Snake River basalts in the northwestern United States.

- Stombolian Eruptions: Rhythmic ejection of incandescent cinder, lapilli, and bombs to heights of a few tens or hundreds of feet (meters). Tephra is glowing red when it leaves the vent but becomes black and nearly solid before hitting the ground. Cinder is most common with less abundant bombs and lapilli. Ash may be present in relatively minor amounts. The tephra accumulates near the central vent and builds a cinder cone. Lava flows may or may not accompany the ejection of pyroclastic material. Magma associated with Strombolian activity is basaltic or andesitic and has a higher viscosity than Hawaiian magmas. Thus, Strombolian flows tend to be shorter and thicker than Hawaiian flows. Named after the Stromboli volcano off the coast of Italy.

- Vulcanian Eruptions: Typically begins with steam explosions that remove old, solid lithic material from the central vent. The main phase of the eruption is characterized by the eruption of viscous, gas-rich magma that forms vitric ash. Vulcanian eruptions can involve almost any type of magma but felsic magma is most common. An eruption cloud, a cauliflower- or mushroom-shaped cloud of ash, develops above the vent. The eruption cloud can be gray or black. Lightning in the eruption cloud is common during Vulcanian eruptions. Airfall, pyroclastic flow, and base-surge deposits can form a cone of ash, surrounded by wide sheets of ash. Tephra deposits from Vulcanian eruptions are more widely dispersed than deposits from Hawaiian or Strombolian eruptions. The eruption of thick, viscous lava flows indicates the end of the eruptive cycle. Named after "Volcano," a volcanic cone in Italy.

- Peleean Eruptions: The two characteristic features of Peleean eruptions are the formation of domes and glowing avalanches. During the opening stages of the eruption, violent glowing avalanches of hot ash travel down the flanks of the volcano. These incandescent avalanches can start fires and are powerful enough to topple walls. Tephra deposits are generally much less widespread than most Vulcanian and Plinian eruptions. Following the initial explosive stage, viscous magma forms a steep-sided dome or volcanic spine in the volcanic vent. Gravity or internal pressure can cause the dome to collapse, resulting in hot block and ash flows. Peleean eruptions are associated with rhyolitic or andesitic magmas and generally complete their eruptive cycle in only a few years. Named for Mt. Pelee in the West Indies.

- Plinian Eruptions: Characterized by an exceptionally powerful, continuous gas-blast eruption and the ejection of large volumes of pumice. Eruptions range in length from days to months. Longer eruptions start with showers of ash (e.g. Pompeii) followed by glowing avalanches (e.g. Herculaneum). In some cases, so much magma is erupted that the summit of the volcano collapses to produce a caldera (e.g. Crater Lake, Oregon). During Plinian eruptions fine ash can be dispersed over very large areas. The eruption of Mount St. Helens in Oregon is a modern example of a Plinian Eruption. Named for the famous Roman naturalist Pliny the Elder who died during an eruption of Vesuvius in A.D. 79.

3.1.4 History of Major Eruptions

Because of its close proximity to civilization the eruptive history of Vesuvius has been well documented. Over 200 powerful eruptions have occurred over the last 2000 years; an average of one eruption every 10 years (*Highton*, accessed 2005)! Some of the more notable historic accounts of activity on the volcano are described below in table 3.1.

Table 3.1: Partial eruptive history of Mt Vesuvius, from 900 BC to present.

Date	**Activity**
900 BC	Some evidence of a tremendous eruption, with dust and ash falling to the east.
320 BC	Vesuvius erupts. Before this, the mountain may have been up to 2745 m in height. During the four centuries before the next eruption, it is covered in forest and, eventually, the volcano is considered dormant.
AD 62	Severe earthquake (5 February) – a warning of the eruption to come. A flock of 600 sheep is swallowed in a chasm. Altitude of Vesuvius may be 1830 m.

Date	Activity
AD 64	Another earthquake rocks the Naples area. Nero, who has just made his singing debut in the theatre there, takes it as a mark of divine respect that none of the spectators has been killed.
AD 79	Vesuvius erupts (24/25 August) violently. Not only are Pompeii and Herculaneum (visited by the emperor Titus only a month before) destroyed; the towns of Stabiae, Oplontis, Sora, Tora, Taurania, Cossa and Leucopetra are also devastated. Titus gives orders for some temple pictures and statues to be salvaged. The top 700 m of the volcano is replaced by a huge crater, and is now called Monte Somma, after Summanus, the god of nocturnal lightning. The new cone that grows on the collapsed side is properly known as Vesuvius.
AD 91	A Roman poet writes about Vesuvius's slopes – once the haunt of "dancing satyrs" but now crowned by flames. This is thought to show the volcano's continued activity.
AD 203	Roman historian Dio Cassius refers to an eruption of Vesuvius.
AD 1036	Vesuvius erupts – the first occasion when lava flow is recorded.
AD 1631	Vesuvius erupts (16 December) with an explosion almost as violent as in AD 79. This is preceded by earthquakes and the drying up of springs. Between 4000 and 18000 die in torrens cineris – "torrents of ash". Vesuvius's crater enlarges from 1.6 km to 4.8 km across. The level of the Bay of Naples drops by 3 m before a wave nearly 5 m high breaks on the shore.
AD 1660	San Gennaro (St Januarius), patron saint of Naples, supposedly causes little black crosses to rain down on villages around Vesuvius. In fact, these are cross-shaped twinned pyroxene crystals torn from the magma and hurled out of the crater.
AD 1707	Vesuvius erupts during the ceremonies marking the taking over of Naples by the Austrians from the Spanish.
AD 1760	Vesuvius erupts. A new crater forms on the side of the mountain.
AD 1767	Vesuvius erupts (29 October) so violently that the king of Naples has to escape at 2 am and the lava just misses the royal palace.
AD 1779	Vesuvius erupts (August). Hamilton writes: "In an instant a column of liquid transparent fire [lava] began to rise.... To the best of my judgement the height of this stupendous column of fire cou'd not be less than three times that of Vesuvius itself, which... rises perpendicularly, near 3,700 feet [1130m] above the level of the sea." The explosion is known as the "centenary eruption" as it occurred almost exactly 1700 years after the disaster of AD 79.

Date	Activity
AD 1794	Vesuvius erupts (June). Hamilton counts 15 separate lava flows. One destroys Torre del Greco. Breislack, an Italian geologist, writes: "[The lava flow's] first direction was towards Portici and Resina, so that the inhabitants of Torre del Greco already bewailed the fate of their neighbours, and began their thanksgivings to the Almighty for their escape. Collected together in the church, they were still singing hymns of joy... when a voice announced to them the fatal news of their approaching destiny." Vesuvius is completely altered, its peak now lower than that of Monte Somma.
AD 1822	Vesuvius erupts. The plume rises to 2 km, ashes fall in Calabria and a volcanic "bomb" of several tons lands in Prince Ottaiano's garden 5 km from the crater.
AD 1855	Vesuvius erupts. It is feared that the lava might even reach Naples (it doesn't).
AD 1872	Vesuvius erupts (April). Projectiles from the volcano shower down, killing medical students climbing the mountain. The entire cone splits. In the years before the next eruption, Vesuvius rises to 1322 m above sea level.
AD 1906	Vesuvius erupts (April). Mountain loses 100 m in height and a vast crater is formed.
AD 1944	Vesuvius erupts (12-29 March). Lava flows through the towns of Massa and San Sebastiano on the north slope. Volcanic "bombs" destroy almost all the Allied military planes at Poggiomarina, and the Germans use the illumination from the eruption to guide their nightly bombing raids on Naples. The cone, which before could be seen from Naples, is flattened and the mountain is lopsided and lower, now 1280 m high.
AD 1980	Pompeii is damaged by an earthquake.

3.1.5 Vesuvius National Park

Vesuvius National Park was founded in 1995 to preserve the geology and ecology of Mt. Vesuvius, the only active volcano in continental Europe. To access the park we will be taking the Circumvesuviana Railway from the Napoli Centrale station to the Ercolano-Scavi station. From there we will take the Transporti Vesuviani to the Park. Our tour of the area will include a visit to the Vesuvius Observatory (the first volcanological observatory in the world).

Directions for Visiting Vesuvius NP

We will visit the exhibit at Vesuvius Observatory at 10:00 AM. Due to changes in the bus service, we will not leave from Ercolano, but from the Pompeii-Villa dei Misteri station of the Circumvesuvia railroad. We need to catch the 9:00 AM bus from Pompeii-Villa station, as the busses only run once per hour. We will have to ask the bus driver for the correct stop, and the observatory is $\sim$300 m from the stop. The observatory staff should be waiting for us. After touring the exhibit, we catch the bus at the same stop for the crater.

3.1.6 Vesuvius Caldera Features

[From *Stefano* (accessed 2005).]

In 73 BC Spartacus led a slave rebellion against Rome. The rebels set up a secure camp at Vesuvius until three thousand Roman soldiers eventually laid siege. At that time the top of Vesuvius was described as being a huge basin filled with a dense growth of vines. Subsequent eruptions have altered the character of the basin dramatically.

A labelled aerial photograph of the crater, including the ancient caldera, is shown in figure 3.2. An example of lava outcrop from the 1944 flows is shown in figure 3.3. Note that the lava is from a lava lake, and hence does not represent the full range of flow regimes on Vesuvius.

Vesuvius Observatory

The Osservatorio Vesuviano was built between 1841 and 1845, surviving several eruptions without damage. It was built on the southern border of the Somma Caldera between two deep valleys that have now been infilled by subsequent lava flows. From the observatory, the lava flows from the 1944 eruption, and the 1895-1899 volcanic activity are visible.

3.1.7 Field Exercise

Become familiar with each of the volcanic terms listed in section 3.1.2. While visiting Vesuvius National Park try to find at least one specific field example corresponding to each term. Note the location of each example and describe it (you may want to also take photographs and GPS references). Compare your observations with those of others in the group. Continue looking for examples of these terms during the Herculaneum and Pompeii days of the trip.

Figure 3.2: An aerial photograph of Vesuvius crater, with the following features labelled: **Somma Caldera** – An 18 ka volcanic caldera in which modern Mt. Vesuvius is built. **Colle Umberto** – A small, densely vegetated lava shield produced by Hawaiian style eruptions in 1895 and 1899. **1944 Lava Flow** – Produced by the most recent eruption of the volcano.

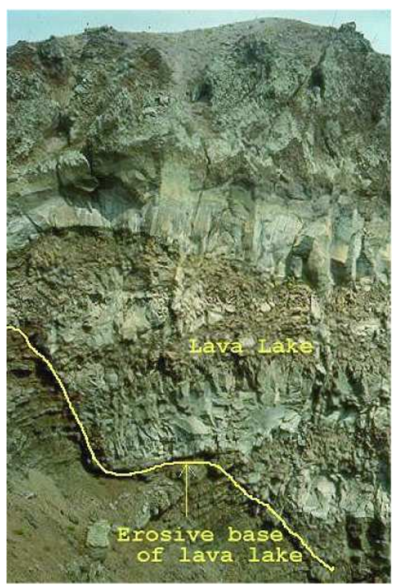


Figure 3.3: Cross-section through a lava lake on the southwest crater wall of Vesuvius; the lake formed during the 1944 eruption. At least four lava flows are visible, each with the typical homogenous center with brecciated top and base. The lava lake unconformably overlies volcanic deposits from previous eruptions.

3.1.8 Additional Contact Information

Park Headquarters
Ente Parco Nazionale del Vesuvio
Piazza Municipio, 8 - 80040 San Sebastiano al Vesuvio (NA)
Tel: 081-771-0911
Fax: 081-771-8215

Circumvesuviana Train Office
Tel 39-081-772-2444

3.2 Herculaneum, etc.

3.2.1 Introduction

From *Stefano* (accessed 2005) and *Flaherty* (1992):

> Herculaneum was destroyed in the AD 79 eruption by a pyroclastic flow. This town, once a beautiful beachside resort, popular with Roman war heroes and nobility. The remains of the grand Roman baths and villas were discovered here in nearly 300 years ago. Until the early 1980s, it was believed that the population of 5,000 had escaped the eruption as only six skeletons had been found in the volcanic debris. However, in 1982, archaeologists unearthed a chamber near to the beach front containing the people of Herculaneum. Hundreds of skeletons have now been exhumed. What shocked the archaeologists is that these people had suffered horrendous burns.
>
> Herculaneum was barely touched by the first eruption as it was being protected by westerly winds (which had been blowing pumice toward Pompeii). Only about one inch of pumice fell on the city during the Plinian phase of the eruption. Nonetheless, many of its inhabitants apparently left. Night fell, lit by the play of lightning around the column billowing skyward. The scene was hypnotic from the close vantage of those who remained in the town. But the watchers were in mortal peril.
>
> At about one o'clock on the morning of August 25, as pressure in the volcano's throat briefly abated, the massive column collapsed, sending a glowing cascade of material down the sides of the mountain. The avalanche quickly separated into two waves. One was a hot, turbulent, fast-moving cloud of lightweight ash and gases (a pyroclastic surge). The other consisted of a denser,

> slower, ground-hugging flow of pumice and larger rock fragments mixed with soil from the slopes and made fluid by temperatures as high as 400[°C]. The front running ash cloud probably descended at a rate of at least 160 kph, taking no more than four minutes to reach Herculaneum and giving those below fruitless seconds to dash in panic toward the sea. Roaring through the city, it ripped off roof tiles, knocked stones askew, and caused the sea to boil when it reached the waterfront. The force of the flow must have been tremendous, the mangled remains of one young woman was discovered scattered across the street. Her skull was sliced in half, and not only was half her skull missing, but her left arm and leg as well.... It was the incredibly high temperatures from this flow that burnt the people of Herculaneum down to their bones.
>
> Herculaneum was utterly dead, and the volcano now proceeded to bury it in a deep grave. Again and again over the ensuing hours – six times in all – Vesuvius belched violently and sent an ash cloud and a trailing wave of rock down on the little seaport, until the buildings lay lost somewhere in the depths of an unrecognizable world.

3.2.2 Stratigraphy of Deposits

[From *Sigurdsson et al.* (1985).]

An example stratigraphic section is shown in figure 3.4; the letter codes refer to the figure.

- Pyroclastic Surge Deposits *(S)* – Hot, turbulent, fast-moving clouds of lightweight ash and gasses. Wide distribution (not controlled much by topography). Form thin, dark-colored bands in the stratigraphic record.

- Pyroclastic Flow Deposits *(F)* – Denser, slower, ground-hugging flow of pumice and larger rock fragments mixed with soil. Narrow distribution and highly controlled by topography. Form thicker, lighter-colored layers in the record.

- S-1 – 20–40 cm of ash from the initial Plinian stage of the eruption (skeletons found on top of this). Most of the basal pumice units present at Pompeii are missing at Herculaneum. Contains carbonized wood and tile fragments.

- 79 Sea Level – Note that sea level has risen substantially since AD 79.

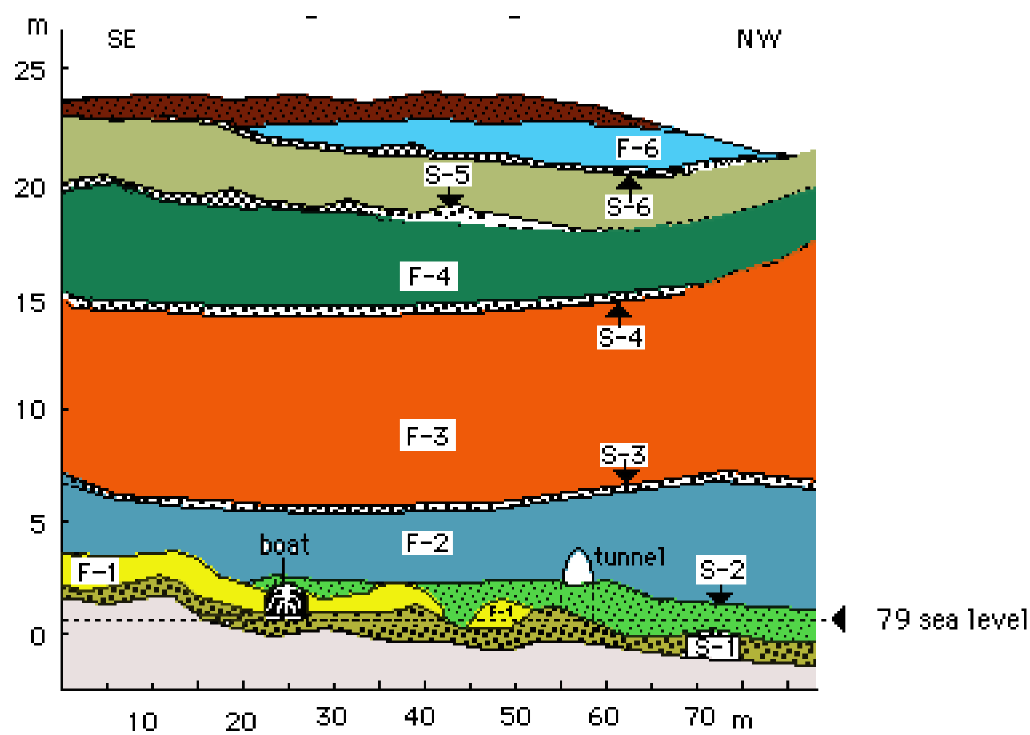


Figure 3.4: Example stratigraphic section at Herculaneum. Units are described in the text.

Figure 3.5: Streets of Herculaneum – "Herculaneum was a residential town in Roman times, it was much smaller than Pompeii. The architecture here is less impressive than at Pompeii, however, the preservation is much better."

Figure 3.6: Shutters and Bed – High temperatures associated with surges and flows produced carbonized wood beams and furniture in Herculaneum.

- Tunnel – After the city was destroyed many tunnels were dug and many things removed. However this soon became very dangerous and the effort was abandoned (*Flaherty*, 1992).

3.2.3 Field Stops

[From *Stefano* (accessed 2005); *Flaherty* (1992); *Scandoni and Giacomelli* (accessed 2005); *Highton* (accessed 2005).]

We will be spending the morning and early afternoon of May 17th at the Herculaneum excavation site (we will travel from Naples to Herculaneum using the Circumvesuviana Railway). Only a portion of this town has been excavated to date, possibly leaving a Forum and other major features of the village undiscovered. Many of the artifacts form both Herculaneum and Pompeii are housed at the National Archaeological Museum in Naples (which we will be visiting later in the day). Below are some of the highlights of the excavation.

3.2.4 Field Exercise

Closely examine the volcanic deposits of Herculaneum. Create a detailed stratigraphic section showing the succession of beds and deposit types. Make sure to clearly label the different rock types which are present. Try to differentiate between pyroclastic surge and flow deposits (see section 3.2.2). Look for and document evidence of ancient sea-level. Note the presence of diagenetic features. If possible, work as a team to measure the thickness of beds

Figure 3.7: Pyroclastic flow deposits – The pyroclastic flow deposits at Herculaneum form a very hard matrix that makes digging difficult (see strat column in figure 3.4).

Figure 3.8: Excavation Tunnels – Several buildings at Herculaneum have tunnels made during the early excavation (1700-1800).

Figure 3.9: AD 79 Sea-Shore – "Before the eruption, the city was situated on a small promontory directly above a beach. This beach is now exposed in the lowest part of the excavations and is currently 4 meters below sea-level. The subsidence of the ancient sea line has been produced by deflation of the volcano after large eruptions. The present retreat of sea coast (250 m) has been caused by the accumulation of volcanic deposits erupted after 79 AD."

Figure 3.10: Neptune Mosaic – The House of Neptune Mosaic is an excellent example of delicate artwork which was preserved by Vesuvius in remarkable condition for future generations. The house all contains a glass case containing three carbonized skeletons (two adult figures and a child). The women's baths are also a must-see when visiting the excavation.

Figure 3.11: Villa dei Papiri – About 1787 papyrus scrolls have been found at the Villa dei Papiri, all badly burned. When some are unwound, they are seen to be written in Greek, mainly philosophical works, with many by the Roman philosopher/poet Philodemus. Researchers at BYU are currently using multi-spectral imaging techniques to decipher parts of the scrolls that were once thought unreadable. It is possible that many more scrolls are waiting to be discovered.

using a Brunton compass and Jacob staff.

3.3 Pompeii

3.3.1 Introduction

[From *Stefano* (accessed 2005) and *Flaherty* (1992).]

> During Roman times Pompeii was a bustling commercial center having streets paved with volcanic stone, gutters alongside carrying away sewage and other filth, lead pipes buried just beneath the surface bringing in fresh water, marble fountains, and lavish houses with spectacular courtyards. But beneath the city tremendous geologic stresses were building up.
>
> In AD 62, the sudden release of pent-up stresses caused the earth to shiver violently. The quake's epicenter was very close to Pompeii, and as the ground heaved, the system of pipes that delivered water to the city were ripped apart. Many villas and smaller houses collapsed, burying people in the ruins. Even worse hit were public buildings, which were constructed of heavier materials and thus less able to ride out the earthquake. "Six hundred sheep were swallowed by the earth" reported the essayist Seneca. "Statues were thrown from their pedestals and smashed, people wandered about completely out of their senses." The damage was so extensive that Nero, the emperor at the time, wondered whether it might not be better just to abandon the place. But the inhabitants did what they could to get Pompeii back on its feet.
>
> Early in August of AD 79, tremors again shook the countryside around Vesuvius. At the same time, a number of wells dried up and springs ceased to flow.... On the 20th day a moderate shock rippled through the area.... Some people, remembering the quake of 62, gathered their belongings and left for safer ground. They were none to soon. During the night of August 23 or the early morning of the 24th, ash began to issue from the volcano, lightly dusting the land downwind. Whatever was happening still seemed fairly innocuous. But about 1:00 P.M., the monster threw off its last restraints.
>
> With a stupendous crack, the floor of the crater gave way under pressure and was blown into fragments, transforming Vesuvius into a giant cannon, its muzzle open to the sky. Molten rock shot 17 miles into the stratosphere, traveling at approximately

twice the speed of sound. Shredded into small particles as it flew upward, it eventually lost momentum, spread out in a flat cloud, and was blown to the southeast by stratospheric winds. Pompeii (and Stabiae) lay in that direction, and the debris started to reign down on them.

The AD 79 eruption had two distinct phases; first a Plinian phase, where material was ejected in a tall column of ash and pumice into the atmosphere. The name is derived from Pliny the Younger who observed and recorded the first eruption seen of this kind in AD 79. The second phase of the eruption was the Peleean phase, where turbulent avalanches of hot gas, ash and pumice flow down the flanks of the volcano at high speeds.

The eruption of AD 79 was characterised by extensive pumice-fall (approximately 2.5 m in Pompeii) from the Plinian phase, followed by a series of six pyroclastic surge deposits. The height of the eruptive column was 15–26 km during the eruption of the white pumice (lower layer) which had a southward trending dispersal axis, and rose to a maximum of 32 km during the eruption of the grey pumice (upper layer) (Martini et al, 1995 [N/A]). The grey pumice partially buried the settlements to the south of the volcano. This tephra fall caused partial roof collapse under the weight of the load, and partial burning of the buildings, but it did not kill the occupants of Pompeii. According to Pliny the Younger, this phase of the eruption lasted no longer than 20 hours. The end of the Plinian phase was marked by total column collapse.

By the morning of the 25th [of] August, most houses in Pompeii were uninhabitable due to collapsed roofs and floors from the tephra load. It is likely that there was a mass evacuation of the city. That morning marked the onset of the Peleean phase. Pliny the Younger reported a very strong earthquake was felt across the region, coinciding with the descent of large clouds of ash. This probably marked the onset of the collapse of the magma chamber roofs. The column collapse generated turbulent pyroclastic flows of gas, ash, and pumice that were channeled in several valleys. The column collapse overrode the present Somma caldera; the pyroclastic flows had nearly a completely radial distribution.

Three of the surges seen at Herculaneum reached Pompeii [S-4, S-5, S-6 in figure 3.4]. *Sigurdsson et al.* (1985) suggested that S-4 would have been the hottest, and most hazardous for humans, whereas S-6 caused more damage to buildings because of its high lithic clast content.

3.3.2 Pliny the Younger's Account

[From *Highton* (accessed 2005).]

Introduction

At the time of the eruption, three significant individuals were staying at Misenum, across the Bay of Naples from Vesuvius. Pliny the Elder, writer on natural history and commander of the Roman fleet, was being visited by his sister and her son, later known as Pliny the Younger. Although he was only 18 years old when the disaster struck, what he experienced then made a deep impression on Pliny the Younger. Many years later, when he was asked by the Roman historian Tacitus to provide an eye-witness description of the calamity for his Historiae, Pliny produced a vivid, hour-by-hour account that has provided valuable clues for present-day volcanologists.

August 24, AD79

1 PM "About one in the afternoon, my mother desired him [Pliny the Elder, the writer's uncle] to observe a cloud of very unusual size and appearance... [It resembled] a pine tree, for it shot up a great height in the form of a trunk, which extended itself at the top into several branches... I imagine, a momentary gust of air blew it aloft, and then failing, forsook it; thus causing the cloud to expand laterally as it dissolved, or possibly the downward pressure of its own weight produced this effect. It was at one moment white, at another dark and spotted, as if it had carried up earth or cinders."

2–3 PM Pliny the Elder sails to get a better view of the disaster and to rescue a friend whose villa is at the foot of Vesuvius (Pliny the Younger decides to remain at Misenum, reading Livy's History of Rome).

"Hastening to the place from whence others were flying, he steered his direct course to the point of danger.... And now cinders, which grew thicker and hotter the nearer he approached, fell into the ships, then pumice-stones too, with stones blackened, scorched and cracked by fire, then the sea ebbed suddenly under them, while the shore was blocked up by landslips from the mountains.... He said to the captain.... 'Fortune befriends the brave: carry me to Pomponianus.' Pomponianus was then at Stabiae, distant by half the width of the bay [of Naples]..."

6 PM Arriving at the house of his friend, Pliny the Elder goes to sleep while the downpour continues. On waking: "They consulted together as to whether they should hold out in the house, or wander about in the open. For the house now tottered under repeated and violent concussions, and seemed to rock to and fro as if torn from its' foundations. In the open air, on the other hand, they dreaded the falling pumice-stones, light and porous though they were; yet this, by comparison, seemed the lesser danger of the two; a conclusion which my uncle arrived at by balancing reasons, and the others by balancing fears. They tied pillows upon their heads with napkins; and this was their whole defence against the showers that fell round them..."

6 PM–12 AM "It was now day everywhere else, but there a deeper darkness prevailed than in the most obscure night.... They thought proper to go down upon the shore to observe from close at hand if they could possibly put out to sea, but they found the waves still ran extremely high and contrary. There my uncle, having thrown himself down upon a disused sail, repeatedly called for, and drank, a draught of cold water..."

August 25, AD79

1 AM Pliny the Younger and his mother have stayed in Misenum, across the Bay of Naples. "That night they [the earthquakes] became so violent that one might think that the world was not being merely shaken but turned topsy-turvy. My mother flew to my chamber.... We sat down in the forecourt of the house..."

2 AM–6 AM "It was now six o'clock in the morning, the light still ambiguous and faint. The buildings around us [Pliny the Younger and his mother] already tottered, and though we stood upon open ground... there was certain and formidable danger from their collapsing. It was not till then we resolved to quit the town..."

8:30 AM Pliny the Elder remains on the shore with his companions: "Flames, and a strong smell of sulphur, which was the forerunner of them, dispersed the rest of the company to flight; him [Pliny] they only aroused. He raised himself up with the assistance of two of his slaves, but instantly fell; some unusually gross vapour, as I conjecture, having obstructed his breathing and blocked his windpipe.... When day dawned again [three days later]... his body was found entire and uninjured, and still fully clothed as in life; its posture was that of a sleeping, rather than a dead man."

Meanwhile, back at Misenum: "A black and dreadful cloud bursting out in gusts of igneous serpentine vapour now and again yawned open to reveal long fantastic flames, resembling flashes of lightning but much larger.... Soon afterwards the cloud... began to descend upon the earth, and cover the sea.... Ashes now fall upon us, though as yet in no great quantity. I looked behind me; gross darkness pressed upon our rear, and came rolling over the land after us like a torrent.... We had scarce sat down, when darkness overspread us, not like that of a moonless or cloudy night, but of a room when it is shut up, and the lamp put out. You could hear the shrieks of women, the crying of children, and the shouts of men; some were seeking their children, others their parents. Some [prayed] to die, from the very fear of dying; many lifting their hands up to the gods; but the greater part imagining that there were no gods left anywhere, that the last and eternal night was come upon the world."

1 PM "At last this dreadful darkness was attenuated by degrees to a kind of cloud or smoke, and passed away; presently the real day returned, and even the sun appeared, though lurid as when an eclipse is in progress. Every object that presented itself to our yet affrighted gaze was changed, cover'd over with a drift of ashes, as with snow..."

3.3.3 Stratigraphy of Deposits in the Pompeii Area

[From *Stefano* (accessed 2005).]

A labelled photograph of an outcrop of the volcanic deposits in the Pompeii region is shown in figure 3.12. Note that the labels are in Italian; translations are provided in the caption.

The opening phase of the eruption left only a few centimetres of pisolitic ash fall and minor surge beds, these deposits are not present in this section.

The start of the Plinian phase consisted of tephra fallout (white and grey pumice layers - Pomici da Caduta) from a sustained column. An initial layer of white pumice, 1.3–1.4 m thick, was followed by a denser grey pumice, 1.1–1.3 m thick. The tephra partially buried settlements in the south. The Plinian phase finished with a total column collapse causing the onset of the Peleean phase.

The Peleean phase is marked by alternating pyroclastic surge and flow deposits. There is an initial 10–20 cm layer of ash from the first explosion. A giant, destructive surge cloud of hot ash swept down the western flank of the volcano and buried Herculaneum. This pyroclastic surge did not reach Pompeii. The surge deposits are overlain by a pyroclastic flow deposit containing carbonised wood and fragments of tiles. This flow deposit varies in thickness from 2 m in the north of Pompeii, to 0.5 m in the south. A final caldera collapse caused the turbulent pyroclastic flows that destroyed Pompeii.

3.3.4 Field Stops

[From *Flaherty* (1992); *Stefano* (accessed 2005).]

We will be spending May 18th at the Pompeii excavation site (we will travel from Naples to Pompeii using the Circumvesuviana Railway). To help

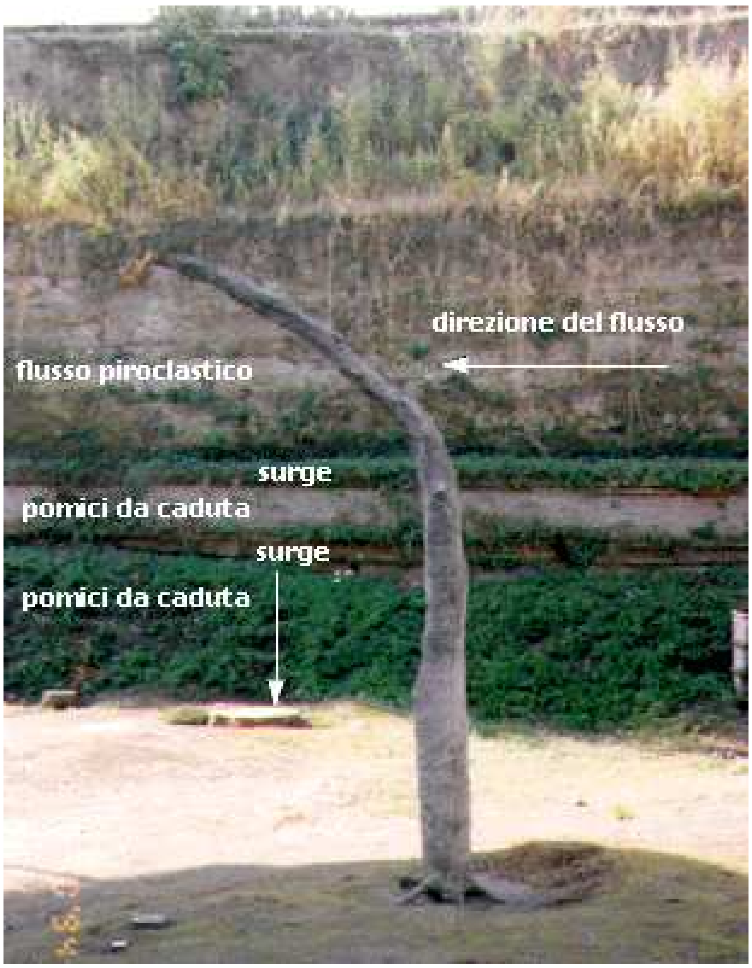


Figure 3.12: Stratigraphy of the AD 79 deposits at Villa Regina, Boscoreale (near Pompeii).
Flusso Piroclastico – Pyroclastic Flow
Direzione del Flusso – Flow Direction
Pomici da Caduta – Pumice

in our wanderings, a map of Pompeii is shown in figure 3.13. Pompeii is perhaps most famous for its plaster casts of victims that give a human perspective to the Vesuvius eruption. In addition, the rapid burial has preserved spectacular artwork and numerous frescos which give a vivid picture of life in Pompeii in the first century AD. Below are a few highlights of this remarkable site.

3.3.5 Field Exercise

Create a detailed stratigraphic column for Pompeii similar to that which was created for Herculaneum. As you will recall the deposits at Pompeii primarily record early phases of the eruption while those at Herculaneum primarily record later phases. Using the information in sections 3.2.2 and 3.3.3 of this guide attempt a correlation of the stratigraphic columns from the two sites. Compare your work with that of other members of the field group.

Compiled by Greg Nielsen, University of Utah, 2005

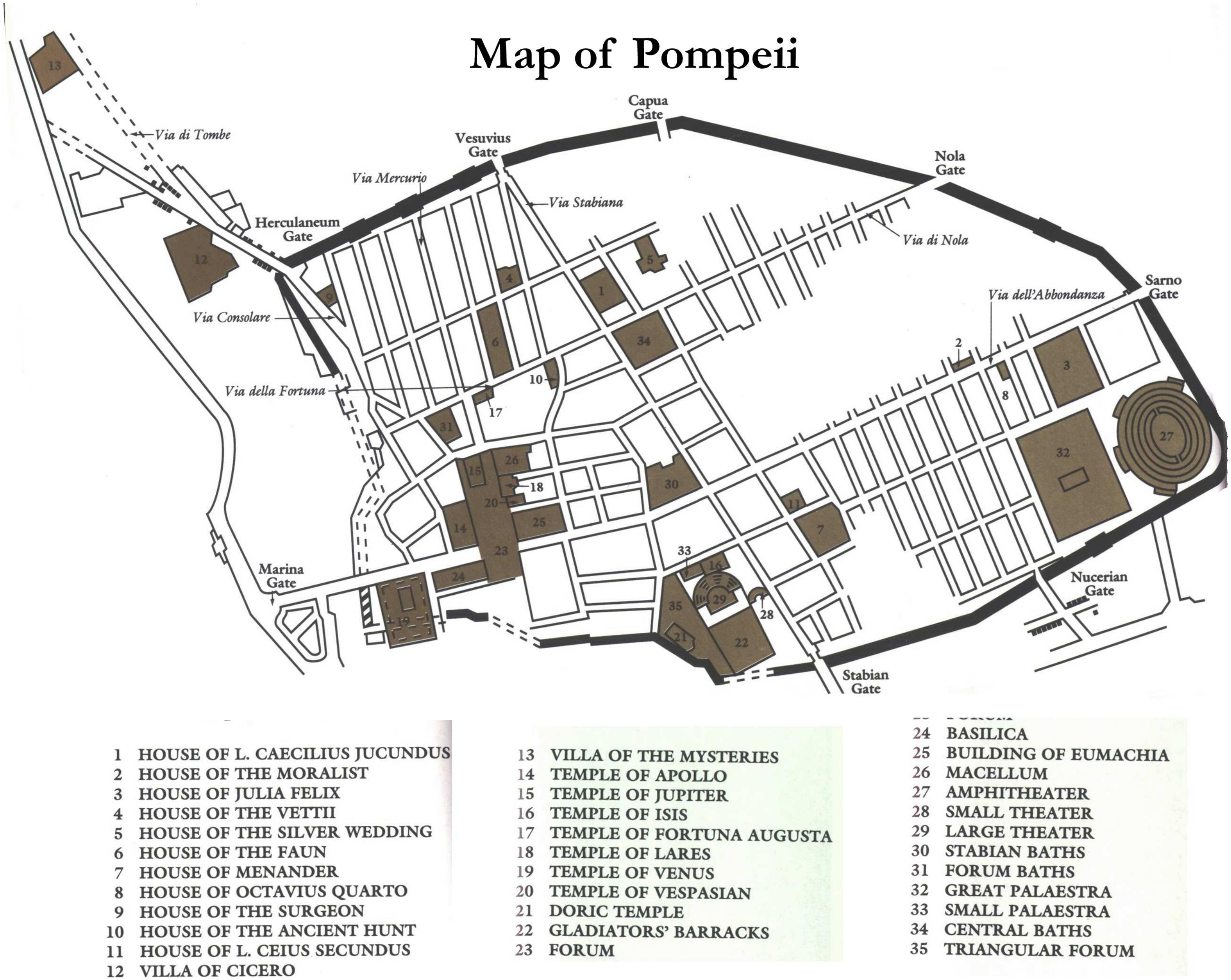


Figure 3.13: Map of Pompeii

Figure 3.14: View of Mt. Vesuvius from Pompeii
"The destroyer and the destroyed." (*Flaherty*, 1992)

Figure 3.15: Pompeii Amphitheatre – The Roman Amphitheatre in Pompeii is the earliest known. In AD 59 (the same year that Nero killed Agrippina, his mother) there was a riot in the amphitheatre, resulting in Nero banning games at Pompeii for a period of ten years.
Image Source: http://members.tripod.com/~mr_sedivy/pompeii_10.html

Figure 3.16: Necropolis of Porta Nocera – Pompeii had a necropolis (cemetery) outside of every gate.

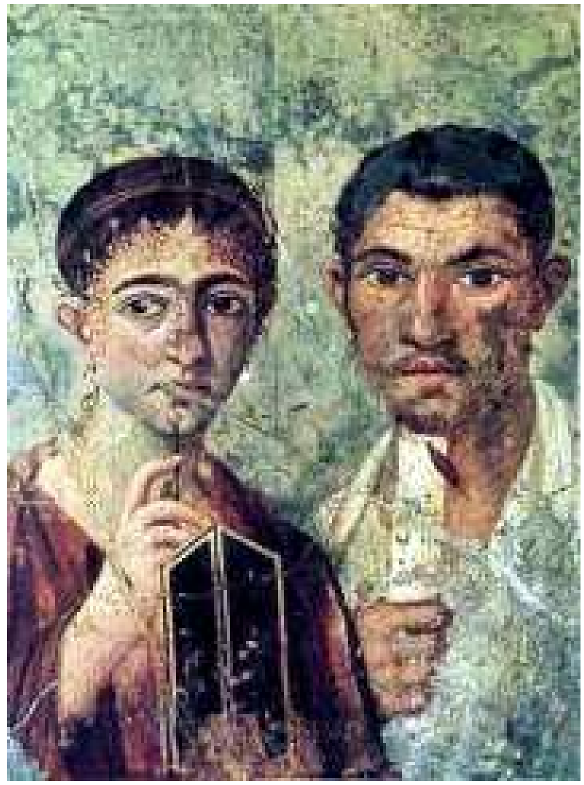


Figure 3.17: Pompeii Fresco – One of many beautiful frescos from a house in Pompeii. Frescos are created by painting walls with wet cement. Many Roman frescos in Pompeii remain intact. Displayed are Pompeian lawyer Terentius Neo (resting his chin upon a scroll) and his wife (holding wax tablets and a stylus). This fresco and many other artifacts from Pompeii and Herculaneum are displayed in the National Archaeological Museum in Naples.

Figure 3.18: Casts of Victims – Created by pouring cement and bauxite in the hardened ash and then chipping away the rock.

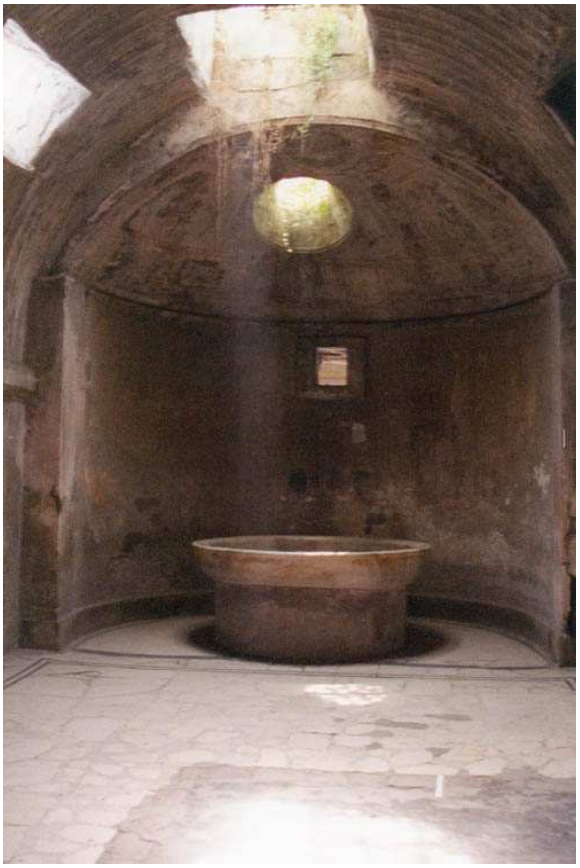


Figure 3.19: Steam Room – A hot steam room from one of Pompeii's Forum Baths. "Patrons normally brought their own bathing tools including a metal pot for oil, scrapers to remove dirt and sweat, and a shallow pot used for interim splashes of cold water."

Figure 3.20: Mosaic – One of many mosaic scenes from the House of the Faun. Pompeii has many well-preserved mosaics which were originally created by piecing together thousands of small pieces of colored tile.

Chapter 4

The Appennines

4.1 Geology of the Northern Apennines

The Northern Apennines is an orogenic stack of tectonic units which has been formed starting from the Late Cretaceous. This orogenic stack involves sedimentary sequences (Tuscan Domain units) originally deposited on the Adria continental margin, as well as oceanic crust and sedimentary successions deposited in the Mesozoic Ligurian-Piedmont Ocean, a branch of the Tethys Ocean. All the units have been deformed as a consequence of the convergence between Adria and Europe (see section 1.4).

Starting in the Late Cretaceous, after the Jurassic ocean spreading, the Ligurian-Piedmont Ocean closed through the development of subduction and an accretionary prism. The shortening started with the deformation of the oceanic realm; these early subduction phases are called “Ligurian”. During the successive “Tuscan” phases, related to the Adria–Corsica-Sardinia continental collision, the already-deformed Ligurian units were transported above the Adria continental margin, where the Tuscan units were being deposited. As a consequence of this collision, the Tuscan units underthrusted the Ligurian and Sub-Ligurian units, which formed the frontal part of the upper plate (Europe) along a west-dipping plate boundary, and experienced ensialic shear. During the ensialic deformation, the continental margin broke up and the Tuscan units developed extensive doubling.

At depth, the underthrusted portions were kinematically metamorphosed. This first tangential deformation phase (D1) has been dated to the Late Oligocene-Early Miocene and is responsible for the main architecture, with the enucleation of two tectonic elements within the Tuscan Domain: the Metamorphic Tuscan Succession and the overlying Tuscan Nappe.

4.2 Siena

Siena is located on a hilltop of porous, shoreface, Pliocene sandstone. It became an important town in medieval times (1100-1400 AD) because it was on a major route for pilgrims travelling from France to Rome along the Via Francigena. It suffered from an absence of readily available water because no large river flows nearby. It was also involved in continuous fights with neighbouring Florence and the territory was not readily defendable. The solution for the medieval town was to build an underground aqueduct consisting of a 25 km-long network of tunnels, called Bottini, which collected water from hills to the northwest and brought it to public fountains (fonti). The underground aqueduct was used for drinking water until the early 1920s. It is now being refurbished to provide water for general use and particularly for watering gardens and city parks.

The objectives of the field trip are to examine the geomorphology and geology to determine the main characteristics of the aquifer (shore sandstones and conglomerates), aquifuge (offshore and lagoonal silty clays), and water potential of the area; to consider the historical-sociological conditions that led to the construction of the underground aqueduct; to marvel at some of the engineering and architectural constructions of the aqueduct itself and at the monumental fountains; and, finally, to savor, albeit briefly, the enchanting atmosphere, architecture, and cuisine of Siena, one of the best preserved medieval towns of Tuscany, in both its buildings and way of life.

[The above summarized from *Costantini and Martini* (2004).]

4.3 Larderello Geothermal Field

4.3.1 Introduction

Larderello geothermal field is a large, produced geothermal system in northern Italy; a location map is shown in figure 4.1. The Tuscan region has a number of geothermal systems, which are thought to be driven by shallow intrusions from the tectonic underplating due to the Europe-Africa collision zone (see section 1.4). These shallow intrusions provide a long-lived source of heat and fluids, which allow for significant production of steam, and hence electricity.

Larderello has been exploited since Roman times, when natural springs were mined for minerals. Modern production is for electric power, using an extensive set of deep (>2 km) wells and steam turbines. While steam extraction has stopped most of the natural vents, power production is sustainable over the long-term so long as injection can continue to maintain the steam reservoir in the rocks under Larderello.

The driving source of the geothermal systems in Tuscany has been studied

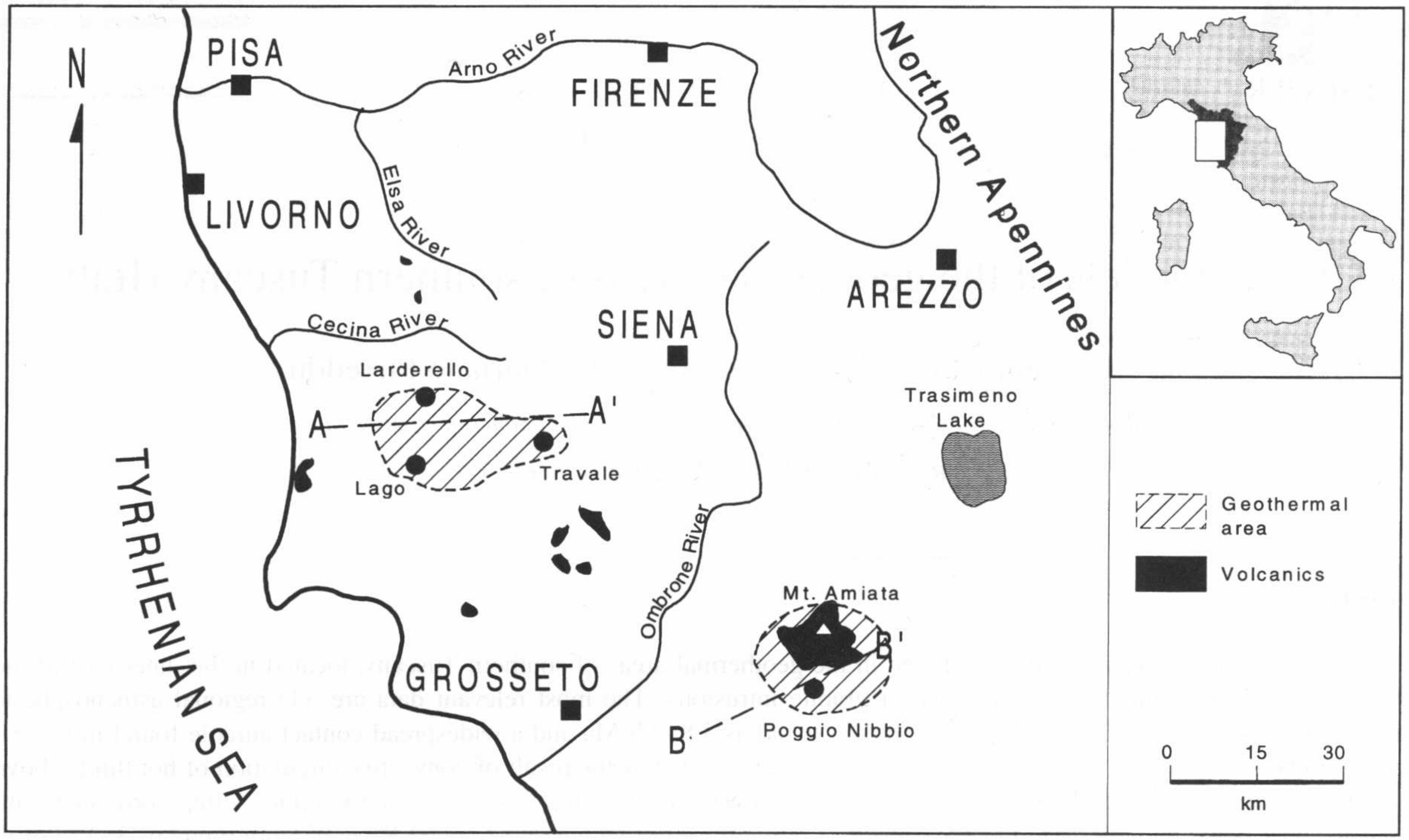


Figure 4.1: Location map of the Larderello geothermal system. From *Gianelli et al.* (1997).

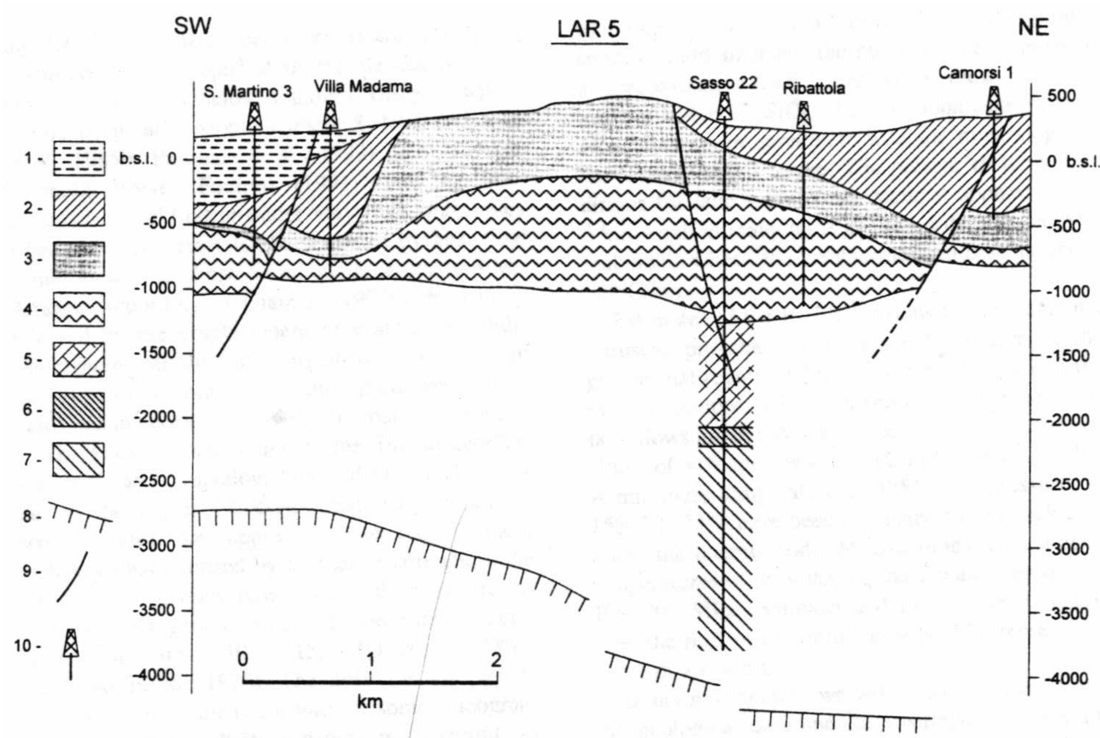


Fig. 2. Geological profile of the Larderello geothermal field: *1* = Neogene sediments; *2* = allochthonous ophiolite and flysch units (Jurassic to Tertiary); *3* = Mesozoic limestone and dolostone; *4* = tectonic slices (Triassic–Palaeozoic); *5* = phyllite and quartzite (Palaeozoic); *6* = micaschist (Palaeozoic to Pre-Cambrian); *7* = gneiss (Palaeozoic to Pre-Cambrian); *8* = the K seismic reflecting horizon; *9* = fault; *10* = geothermal well. After Batini et al. (1985a).

Figure 4.2: Example section of the upper crust under the Larderello geothermal system, based on drill cores. From *Gianelli et al.* (1997)

using a wide variety of methods, including drilling, geochemistry, gravity, heat flow, and seismology.

4.3.2 Geology & Geophysics of Larderello

The upper 4–5 km of the Larderello region is well-known, due to the large number of wells that reach these depths. Drill cores show the region to consist of sequences of sedimentary, metamorphic, and igneous rocks (surface to depth); an example section is shown in figure 4.2. This sequence is not unexpected in age, order, or thickness, given the tectonic history of the northern Apennines (recall the brief dicussion in section 1.4). A more detailed geology of the cores and region, including references to the original papers, is given in *Gianelli et al.* (1997).

All Tuscan geothermal fields show evidence of recent high-temperature (HT), low-pressure (LP) metamorphism. Fractures in the host rock are filled with HT minerals, with indications of minimum formation temperatures of

350°C. Some assemblages indicate maximum temperatures of nearly 600°C. The filled joints and fractures cut across pre-existing textures in the host rock, and are likely due to the emplacement of the granite intrusions.

Seismic reflection surveys consistently show a strong reflector near the base of the brittle crust, which represents a sharp decrease in impedance. This reflector, named K, shallows to 3-6 km below the Larderello field, but is 10-12 km in Tuscany outside the geothermal areas. The K reflector has only been intersected by one drill core, which found shattered biotite and tourmaline-rich micaschist. Bottom hole conditions were estimated to be an equilibrium temperature of 450°C and fluid pressure of 24 MPa (240 bars) at 2900 m depth. Thus, the K reflector likely represents a region of fractured, fluid-filled rock around and inside the granite intrusions. Gravity and magneto-telluric (MT) data across the Larderello field indicate a low-density, conductive body under the field; best fit 2- and 3-D models show a depth range for the body of 7–20 km.

The gravity, seismic, and MT data are all consistent with a granitic intrusion (or set of intrusions) between 7 and 20 km in depth, with regions of partial melt, and a zone of highly fractured, fluid-filled rock forming a halo around the main body. Convective circulation in the fractured halo gives rise to the strong K reflector, and moves heat upward into the country rock. Circulation of meteoric water from the surface, mixing with small amounts of metamorphic water leaking up from depth, bring heat and minerals to the surface and drive the Larderello steam field.

[The above section summarized from (*Gianelli et al.*, 1997).]

4.3.3 Power Production

General Overview of Geothermal Power Production

Geothermal power plants produce power by extracting hot steam from the ground, and using the pressure and temperature to drive a turbine, which drives a generator. The cool, low-pressure steam that comes out the back of the turbine is either lost to the air (old system), or reinjected into the reservoir rock (all current systems); many modern systems also condense the low-pressure steam before reinjection. When we tour the Larderello geothermal system, pay attention to the large towers with steam wafting out the top; these are cooling towers, where cold water is used to liquify the steam coming out of the turbines. The actual power production is done in the turbine building, which is generally a non-descript box of a building next to the cooling towers.

By condensing the steam, two benefits are realized. First, the liquid can be reinjected, conserving mass in the geothermal system, which maintains the resource; most geothermal systems become unproducable due to a lack of steam, not a lack of heat. Second, condensing the vapor greatly drops the pressure at the exhaust of the turbine, which allows the turbine to extract more energy from the incoming steam (greater pressure differential). The pressure benefit is only realized in a direct-contact power plant. Direct-contact plants, due to losses in the cooling towers, cannot recycle all the extracted steam; typical recovery rates are >90%. There are also (smaller) geothermal plants that run by using a heat exchanger to transfer heat from the incoming steam to a working fluid in a sealed system. The working fluid drives the generators, and the cooled steam is reinjected. The sealed fluid system allows for a small plant footprint with no cooling tower or vortex separators.

Note that many geothermal systems do not produce "dry steam"; that is, there is some liquid mixed with the vapor that comes out of the production wells. Water, and the minerals dissolved in it, will stick to the turbine blades, throwing them off balance, and causing them to rip apart at speed. Hence, geothermal systems with "wet steam" will pipe the incoming steam/water mix into a vortex separator to drain the water and extract pure vapor to feed the turbines. Depending on the conditions at Larderello's wells, we may see a vortex separator in the steam lines, although the field has historically been very "dry".

Production at Larderello

The first known exploitation at Larderello was by the Romans, who used the natural sulfur springs at the field. During the 18th and 19th centuries, boric acid was extracted from the natural hot springs for industrial use. Power production began at Larderello in 1904 with the installation of a steam dynamo powering 5 light bulbs. This is also the first geothermal power production in history. In 1913, Larderello started its' first geothermal power plant, a dry steam turbine. Since then, Larderello has been a geothermal power producer, although at small scales prior to 1963. Since the 1960s, production and exploration have expanded greatly to a current output of ∼800 MWe (MW electric). This represents roughly 10% of the current geothermal power production in the world.

4.4 Cinque Terra

4.4.1 Introduction

The western promontory of the La Spezia Gulf and its northward prolongation along the Ligurian Sea is an excellent area to study the sedimentary and deformational history of the Northern Apennines. One of the most spectacular geological cross-sections of the Apennines is visible on the cliffs along the coast with outcrops of units of the Mesozoic Tethys Ocean domain and of the

Mesozoic to Cenozoic basins of the Adria continental margin. These units record significant deformations from the Jurassic ocean spreading phase to the Late Cretaceous-Miocene subduction and collisional phases.

The cruise will start from La Spezia and our final stop, before coming back to La Spezia, will be at Monterosso. We will first cross the La Spezia fold, a pluri-km structure that involves the Adria margin units (Tuscan Nappe). Then we will enter the oceanic realm, the Ligurian Domain.

During the present field trip the structural framework will be described and discussed through the beautiful exposures of the steep Cinque Terre sea-cliffs. The Cinque Terre (Five Lands) is a district with five coastal villages: from north to south, Riomaggiore, Manarola, Corniglia, Vernazza and Monterosso. During a thousand years of work, peasant farmers have transformed an impervious territory into fertile terraces for the production of famous white wines. Until the 1950s, only mountain paths and the railway connected these villages. Now they are crowded tourist resorts and a national park has been set up to protect the natural riches of the Cinque Terre, a UNESCO World Heritage site.

4.4.2 Geology

As we will see in all its' spectacular sea cliff exposures, the La Spezia fold involves the Tuscan Nappe, but also some of the Sub-Ligurian units. In this area, some Ligurian units' deformation features could have been associated to the event that produced the La Spezia fold. The peculiarity of the La Spezia fold is that its SW direction of tectonic transport is opposite to the general NE vergence of the Apennine fold and thrust structure. This anomalous feature has inspired several models not only for the La Spezia fold but also for a more general model of the evolution of the northwestern sector of the Northern Apennines. These models can be referred to as "compressive" or "extensional". The difference between the two interpretations is substantial. In the compressional model the La Spezia fold would have developed during the collisional D1, NE-verging (Adriatic) phase, and its' SW (Tyrrhenian) vergence would have been the result of unusual situations – for example a shear system dominated by strike-slip movements, pop-ups, or back slides. The extensional model maintains an initial NE-verging (Adriatic) phase, but ascribes the fold to a subsequent post-collisional phase characterized by exhumation and gravitational collapse toward the SW.

On the basis of new structural investigations and reassesments of available data, we can pin down the following four elements as significant for the reconstruction of the deformational history of the La Spezia fold: (1) a pre-folding cleavage; (2) the main axial cleavage of the La Spezia fold, which does not match the pre-folding cleavage, and that is associated, instead, with a D2 compressional event; (3) a mineral recrystallization along the D2 cleavage/schistosity attesting to a pressure of 170-230 MPa and a temperature of 250-290°C during the folding; and (4) a third cleavage associated with folds formed at shallower structural levels, but still coaxial with the La Spezia fold. In the view of *Papini and Vannucchi* (2004), the La Spezia fold developed during the D2 compressional phase as a deep SW backthrust in the NE-verging fold-and-thrust belt. The whole edifice has been lately deformed by low-angle extensional features and cut by steep normal faults.

Here is a general description of the main tectonic units cropping out in the western promontory of La Spezia and in the Cinque Terre district. From top to bottom, they are: the Gottero Unit and the Ottone Unit, representing respectively the Internal and External Ligurian Domain; the Canetolo and the Marra Units of the Subligurian Domain; and the Tuscany Nappe.

The Ligurian Domain

The Jurassic to Paleocene Ligurian units are mainly cropping out in the promontory of Punta Mesco (Monterosso) and will be examined in the final part of our field trip. These units represent the sedimentary sequences deposited in the Ligurian-Piedmont Ocean and their ophiolitic basement. Northern Apennine ophiolites are thought to represent the oceanic lithosphere of the Ligurian-Piedmont basin.

In the Ligurian Domain it is possible to distinguish Internal Ligurian units, originally deposited adjacent to the European Corsica-Sardinia massif, and External Ligurian units, which were deposited closer to the Adriatic continental margin.

Starting from the Early Cretaceous, the Ligurian Units were so intensely involved in the Apennine orogenesis that the external part of this domain has detached from its original oceanic basement causing an intense disruption of its lithostratigrafic succession. Thus, the External Ligurian units exhibit ophiolitic rocks only as intercalated blocks of tectonic or gravitational origin, attesting to the involvement of the basement in the Apennine orogenesis. Conversely, the Internal Ligurian units maintain, at least in some cases, stratigraphic relationships with their ophiolitic basement.

The Sub-Ligurian Domain

In the area that we are going to examine the Sub-Ligurian Domain is mostly represented by the Canetolo Unit. The high degree of deformation showed by this unit, and by the Sub-Ligurian Domain in general, prevents the reconstruction of a sound stratigraphic succession. The Canetolo Unit is an association of Paleogene sediments with a prevailing argillitic component and a calcareous-rich lower portion, while presenting an upper part with abundant sandstones. The basement of the Sub-Ligurian Units is unknown, but the petrographical, sedimentological, and stratigraphical analyses performed on the sedimentary sequence, as well as paleogeographic reconstructions, suggest a basement formed by thin, transitional oceanic/continental crust. In the Cinque Terre area the calcareous portion (Groppo del Vescovo Limestones) and the sandstones (Ponte Bratica Sandstones) are bound by tectonic contacts and exhibit intense internal deformation. The result is a unit of variable thickness, discontinuously overlapping the Tuscan Domain. Frequently tens-of-meters-thick lenses of Oligocene marls and siltstones are tectonically interposed between the Canetolo Unit and the Tuscan Nappe. These lenses, referred to as the Marra Unit, most likely represent slope deposits.

The Tuscan Domain

The Tuscan Domain consists of a thick (3–4 km) sedimentary succession widely exposed in the Northern Apennines. The Tuscan Domain developed on the continental Adria passive margin from the Triassic throughout the whole Miocene, and was deformed during the Miocene collisional phase of the Africa-Europe convergence. As a consequence of this collision, the internal portion of the Tuscan Domain underthrusted the external part, causing a tectonic doubling of the succession. Sandwiched in between the two units there are tectonic breccias. The underthrusted portion has been metamorphosed (Metamorphic Succession of Punta Bianca) and is extensively cropping out in the eastern promontory of the La Spezia gulf. The unmetamorphosed portion constitutes the Tuscan Nappe, and is the backbone of the western promontory of the La Spezia gulf. Above a terrestrial Triassic sedimentary succession (not to be examined during this field trip) rest widely-extended carbonate platform deposits, in progressive subsidence, exposed along the Portovenere-Cinque Terre coastal area. During the Middle Jurassic the platform drowned and the sedimentation environment became pelagic. Finally, with the start of the collision, an Oligocene foredeep was set up. The arenaceous turbiditic sedimentation of this foredeep is well represented in the area of the field trip.

[The passage above is modified from *Papini and Vannucchi* (2004).]

4.4.3 Exercise

Measure several sedimentary sections, concentrating on the turbiditic sequences. Also, we will try to recognize a typical Bouma sequence (see figure 4.3) and the section of the turbidite fan we are in (upper, middle, lower; see figure 4.4).

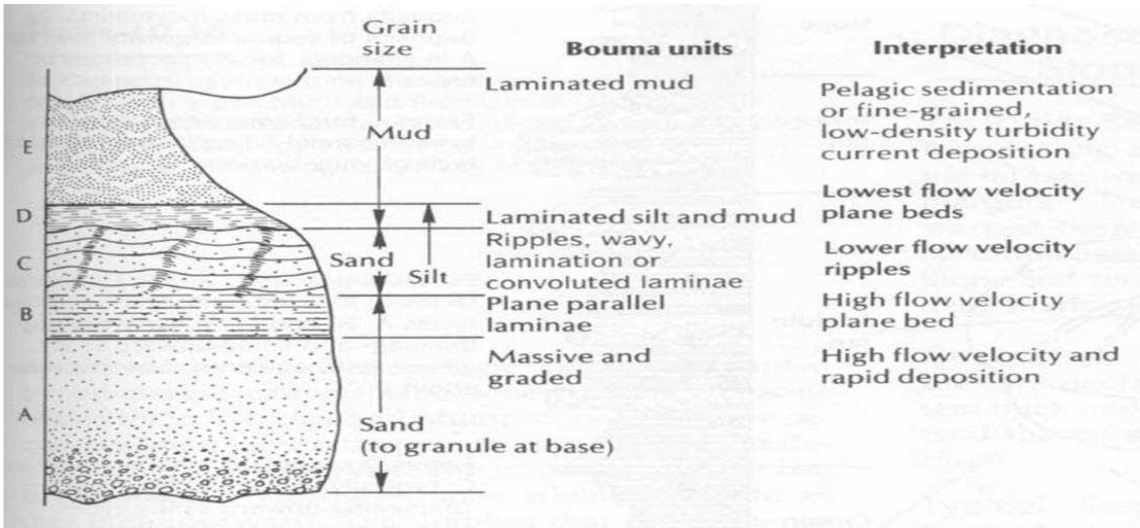


Figure 4.3: Typical Bouma sequence in Cinque Terra.

4.5 Val Graveglia

4.5.1 Introduction

The Graveglia Creek, part of the Entella River Basin, is located in the inland Tigullio area, a few kilometers northeast of Lavagna. The Graveglia Valley (in Italian Val Graveglia) covers an area of about 60 km^2. The industrial mining of manganese developed there during the 19th century and is continuing today on a very small scale. The deposits are rather small, but have yielded over 125 mineral species to date, some of which are remarkable for beauty or rarity. The manganese district of Val Graveglia in northern Italy produced over 1 000 000 tons of high-grade ore in about a century of operation, reaching a maximum production rate of about 50 000 tons/year.

Val Graveglia is the type locality for eight minerals (ravegliaite, medaite, palenzonaite, reppiaite, saneroite, strontiopiemontite, tiragalloite and vanadomalayaite), and is one of the few reported localities for several other rare species including gamagarite, marsturite, nabiasite, haradaite and pyrobelonite. This deposit has also produced exceptional specimens of tinzenite, sursassite and ganophyllite.

Manganese is the twelfth most abundant element in the Earth's crust. Manganese deposits are generally of sedimentary origin, as oxide ore layers interbedded with iron-rich formations, as carbonate ore in black carbonaceous shales, and as nodular ores. Nodules and crusts can form in soil profiles along weathering surfaces, in shallow marine sediments, and on the deep seafloor. Huge concentrations of manganese are often associated with seafloor "black

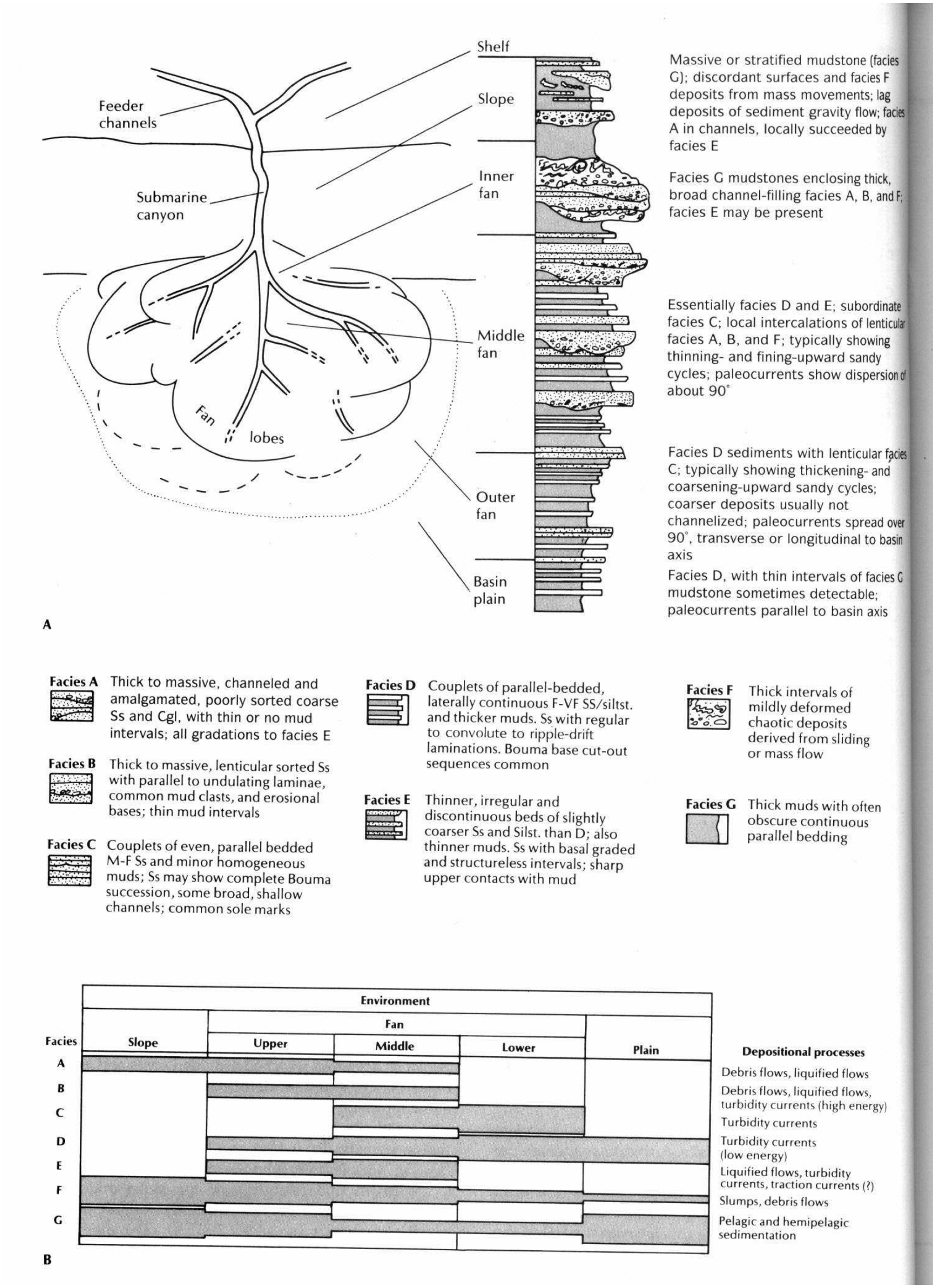


Figure 4.4: Turbidite facies for different parts of the fan.

smokers", which represent the surface expression of hydrothermal systems.

Manganese has been used in small amounts since antiquity, but not until the 1850's were the valuable properties of manganese in iron and steel metallurgy recognized, and the metal finally used in industrial applications. A huge increase in manganese demand occurred in the second half of the 19^{th} century, and many mines were opened. Today's world demand, mainly from the steel industry, is around 25 000 000 tons/year.

Manganese deposits are often of great interest from a mineralogical point of view: the peculiar electrochemistry of this element and its geochemical association with other elements such as arsenic, barium, iron, lead, vanadium, and zinc play an important role in the formation of many interesting and occasionally fine minerals.

The Val Graveglia mines left a deep mark on the environment and on the people of the valley. In the villages of the rocky upper valley, where the farm land is limited, almost all families had members working in the mines. Mine workers numbered 50 to 100 in 1937, then grew to 500 in 1938, to 614 in 1942, and then decreased to 110 in 1974, when large-scale mining activity ceased. Many pits, excavations, mine dumps, some remains of cableways, hoppers, ore treatment plants, and roads are still visible and testify to the past of a region which hosted an important manganese deposit.

4.5.2 Geology

An ophiolitic suite consisting of ultramafic rocks, usually highly serpentinized and associated with mafic masses, crops out in the Northern Apennines at Val Graveglia. The upper part of the complex includes breccias containing fragments of ultrabasic, basic and trodhjemitic rocks, and basalts, often with pillow structures.

Above the ophiolites is a complex of radiolarian chert and siliceous shale known as the Monte Alpe Chert Formation. The series continues with marls, siliceous shales and pelagic limestone (Calpionella Limestone), and ends with the Palombini Shale and turbiditic units. The ophiolites are believed to be the remnants of some part of the Jurassic oceanic crust, known as the Ligurid Units, which now constitute the structurally highest part of the Apennine chain. Many events leading to the formation of minerals and ores occurred during a geological history of about 100 million years.

An oceanic metamorphic event transformed the gabbros into rodingites, while iron and copper sulfides were deposited by hydrothermal activity. Hot-fluid vents deposited a high concentration of manganese on the Jurassic sea floor, presently appearing as manganese ore deposits within the Monte Alpe Chert formation.

All the rocks of the series recrystallized under greenschist metamorphic conditions during the Alpine orogeny. The pre-existing sulfides were remobilized and formed Cu-Fe deposits. Moreover, some elements present in low concentrations in the rock mass were concentrated in the rock fractures by fluids. The complexity of the geological and petrologic environment, the abundance of fractures along the shear zones and at the hinge zones of the folds, together with the presence of manganese, vanadium, arsenic and many other elements made possible the formation of many interesting minerals.

In the peridotitic basement rocks a few species are present, such as serpentine-group minerals, magnetite, and andradite. In the pillow lava, metamorphosed under greenschist conditions, cavities up to 20 or more centimeters are common, often partially filled by epidote, prehnite and quartz, all of them commonly in good crystals. Calcite, pumpellyite and hematite are also widespread. Along old faulting zones small masses of pyrite (often copper-bearing) are present. These marginal deposits were explored and mined mainly during the 19^{th} century. In the old workings several secondary minerals were found, including nice malachite and allophane.

The radiolarites formation of Monte Alpe is undoubtedly the most mineralogically interesting in the area. In the basal part of the formation the manganese-bearing layers form a banded ore known as "lean manganese ore," which is quite common. The formation of layers of cherts with different silica, iron, and manganese contents seems to be related to variations in pH and Eh values at the time of the deposition. The "lean ore" is sometimes crossed by veins up to 80 cm wide and up to several tens of meters in length; this kind of vein yielded carpholite, native copper, sulfides, and probably the world's best specimens of tinzenite, sursassite and ganophyllite.

The same stratigraphic basal unit of the Monte Alpe Formation also includes the main manganese orebody, formed by braunite layers. The thickest layers, up to 20 m, are thought to have possibly formed by gravitational accumulation of pre-existing Mn-rich sediments, which were concentrated in paleogeographic depressions. Further increase in thickness occurred in the hinge areas during folding. The braunite ore is relatively rich in veins and vugs containing good specimens of rhodonite, rhodochrosite, tephroite, kutnahorite, pyroxmangite and barite.

In the orebody veins the circulating fluids concentrated elements such as arsenic and vanadium, which formed many minerals, some of which were discovered here for the first time (tiragalloite, medaite, saneroite, palenzonaite, vanadomalayaite, reppiaite) or which are rare or uncommon (haradaite, tangeite, sussexite, gamagarite, goldmanite). The crystallization of the arsenic-bearing and vanadium-bearing minerals could be related to a hydrothermal event taking place under conditions of decreasing temperature with respect to greenschist conditions recognized in the ophiolitic sequence. The new mineral gravegliaite, a rare natural sulfite, occurs in secondary suites.

A very peculiar occurrence of minerals in Val Graveglia must also be noted: within the Jurassic-age radiolarites it is sometimes possible to find silicified (petrified) woods belonging to trees of the extinct genus Araucariopitys. This is an unexpected occurrence; the radiolarites are considered to be equivalent to the present-day muds in the oceanic or marine sea floor, which was not a likely environment for typical continental plants to grow. According to recent studies, during the Jurassic period the paleogeography of the area would have been quite complex, and perhaps some islands hosted primitive trees. Some timbers or wood fragments, after floating for some time and distance on the sea surface, may have sunk in the proximity of sea vents, where there was an abundance of dissolved metal ions. This particular environment permitted the preservation of the wood; the pH and Eh conditions caused the partial replacement of the wood material, and in particular the deposition of native copper or chalcocite in the wood microcavities. Later, during the recrystallization of the rock mass, more minerals formed. Finally, secondary minerals formed. In the fossil wood many mineral species have been found, including copper, chalcocite, volborthite, cornubite, chalcophyllite, zeunerite, connellite and many others. It is interesting that significant amounts of Cu, V, As, Cl and even U probably originated from the hot-water sea vents. This occurrence seems to be specific to eastern Liguria and is not known in the very old manganese deposits, which were formed before the development of trees on earth.

[The above is modified from *Marchesini and Paqano* (2001).]

4.5.3 Exercise

Measure a section of ophiolite. Attempt to recognize all of the characteristic parts of an ophiolite sequence, including (in stratigraphic descending order): seafloor sediments (pelites and/or chert), pillow basalts, sheeted dike complex, undeformed gabbros, layered and foliated gabbros, peridotie. See figure 4.5 for details.

4.6 Alpi Apuane

4.6.1 Introduction

Alpi Apuane are one of the most original mountain areas in Italy, for the variety of their landscape and environments. The ancient presence of human settlements has left important historical and cultural traces in the area. Alpi Apuane are known all over the world for the beauty of their precious marbles and other decorative and building stones ("cipollino", breccias, Cardoso stone). The Apuane are an orographic complex of great charm thanks to their massive mountains, the harsh morphology, the deep valleys, and the very steep slopes. Within a few kilometers from the small coastal plain in

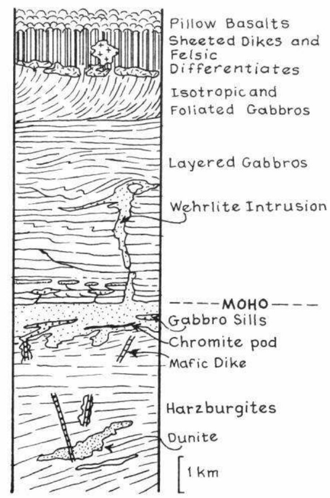


Figure 4.5: Example ophiolite section.

Versilia, the Apuane rise to almost 2 000 m high at the top of Mt. Pisanino (1947 m).

The area presents remarkable geomorphological features: well-preserved morraines, erratic boulders, valleys, and cirques dating back to the last glaciation. On the surface, there are karst phenomena like carted fields, dolines (Carcaraia, Mt. Altissimo, Mt. Sagro, etc.) and other epigeal dissolution phenomena (Vetricia plateau, Mt. Forato arch, etc.). In the underground there are some of the main expressions of the karst phenomena: deep abysses and the great cavities of the Apuane, resulting from an incredible labyrinth of tunnels and wells: the Antro del Corchia – for instance – has a total length of over 70 km of subterranean channels and 1210 m of elevation change; it is the main karst system in Italy and one of the biggest in the world.

[from http://www.parks.it/parco.alpi.apuane/Epar.html]

4.6.2 Geology

Geological Setting of the Alpi Apuane

Within the Alpi Apuane region, three different tectonic units derived from the Tuscan domain are traditionally distinguished:

- the Tuscan nappe
- the Massa unit
- the “Autochton Auct.” unit

The Tuscan nappe

The Tuscan nappe consists of a Mesozoic cover detached from its original basement along the decollement level of the Norian anidrites and dolostones, now transformed almost totally into cataclastic breccias called Calcare Cavernoso ("cellular" limestone). The sequence continues upward with Rhaetian to Hettangian shallow water limestones (Rhaetavicula Contorta, Portoro, and Massiccio), Lower Liassic to Cretaceous pelagic limestones, radiolarites, and shales (Calcare selcifero, Marne a Posidonomya, Diaspri, Maiolica), grading to hemipelagic deposits of the Scaglia (Cretaceous-Oligocene) to end with siliciclastic foredeep turbidites of the Macigno (upper Oligocene-lower Miocene).

The entire sequence with a variable thickness between 2–5 km in the Mesozoic carbonate part shows strong lateral and longitudinal variability related to an irregular and locally rugged paleogeography heritage of block faulting and fragmentation of the passive margin during the Liassic-Early Cretaceous rifting stage, but also related to the weak Cretaceous-Eocene tectonic inversion produced by the northward movement of the Adriatic plate and the far field contractional tectonics related to the inception of the Ligurian ocean closure.

Peak metamorphic conditions do not exceed the anchizone/subgreenschist facies conditions with estimated temperature around 250-280°C on the basis of vitrinite reflectance (value around 5.1), illite crystallinity, isotope studies, and fluid inclusion analysis.

The Massa unit

The Massa unit, exposed in the southwest part of the Alpi Apuane, is characterized by a pre-Mesozoic basement and a middle to upper Triassic cover. The pre-Mesozoic basement is formed by upper Cambrian-lower Ordovician phyllites and quartzites, middle Ordovician metavolcanics and metavolcanoclastic sediments (porphyroids and porphyric schists) associated with quartzic metasandstones and phyllites, and rare Silurian Orthoceras-bearing metadolostones and black phyllites.

The Mesozoic cover sequence consists of a metasedimentary mid-upper Triassic sequence ("Verrucano Fm") characterized by the presence of middle Triassic metavolcanics. The metasedimentary sequence is formed by quartzose clast-supported metaconglomerates associated with metasandstones, metasiltstones, and black phyllites overlain by marine deposits (Ladinian crynoidal marbles, carbonate metabreccias, calcschists and phyllites) intercalated with alkaline metabasalts (prasinites and green schists). Upwards the succession ends with a transgressive continental cycle consisting of coarse-grained quartzitic metarudites ("anageniti"), quartzites, and muscovite phyllites.

The basement rocks in the Massa unit show evidence of a pre-Alpine greenschist-facies metamorphism which has been ascribed to the Variscan (Hercynian) orogeny. The Alpine metamorphism (as investigated in the Mesozoic cover rocks) is characterized by kyanite+chloritoid+phengitic muscovite assemblages in metapelites. Peak conditions have been estimated in the range of 0.6-0.8 GPa and 420- 500°C.

"Autochthon Auct." unit

The "Autochthon Auct." unit is made up of a Paleozoic basement unconformably overlain by the Upper Triassic-Oligocene metasedimentary sequence. The Paleozoic basement is formed by the same rock-types of the basement in the Massa unit, but here they are exposed in larger and clearer outcrops: upper Cambrian-lower Ordovician phyllites and quartzites, middle Ordovician metavolcanics and metavolcanoclastics, upper Ordovician quartzic metasandstones and phyllites, Silurian black phyllites, Orthoceras-bearing metadolostones, and lower Devonian calcschists; moreover the upper Cambrian-lower Ordovician phyllites and middle Ordovician metavolcanics contain several thin lenses of alkaline to subalkaline metabasites corresponding to original dykes and/or mafic volcanoclatic deposits (*Gattiglio and Meccheri*, 1987; *Conti et al.*, 1993).

Also the basement rocks in the "Autochthon Auct." unit recorded a pre-Alpine deformation and greenschist-facies metamorphism as the Massa unit (*Conti et al.*, 1991), for which the most striking evidence is the regional angular unconformity at the base of the oldest Mesozoic formation (Triassic Dolomite) stratigraphically lying on almost all the Paleozoic formations.

The Mesozoic cover-rocks include thin Triassic continental to shallow water Verrucano-like deposits followed by Upper Triassic-Liassic carbonate platform metasediments comprised of dolostones ("Grezzoni"), dolomitic marbles, and marbles (the "Carrara marbles"), which are followed by Upper Liassic-Lower Cretaceous cherty metalimestone, cherts, and calcschists. Lower Cretaceous to Lower Oligocene sericitic phyllites and calcschists, with marble interlayers, are related to deep water sedimentation during downdrowning of the former carbonate platform. The Oligocene sedimentation of turbiditic metasandstones ("Pseudomacigno") closes the sedimentary history of the domain.

The Alpine metamorphism in the Apuane unit is characterized by pyrophyllite + chloritoid + chlorite + phengitic muscovite in metapelites. Peak-metamorphic conditions have been estimated by this assemblage in the range of 0.4-0.6 GPa and 350-450°C (*Franceschelli et al.*, 1986; *Di Pisa et al.*, 1987; *Jolivet et al.*, 1998; *Molli et al.*, 2000). *Di Pisa et al.* (1985) first recognized, through a calcite/dolomite investigation, temperature variations from southwest (Ca/Do temperature up to 450°C) to central and northeast part (Ca/Do of 380-350°C). Such data have recently been confirmed and used to interpret part of the microstructural variability in marbles (see below).

The regional tectonic setting of the Alpi Apuane is well known and generally accepted by researchers belonging to different geological schools. On the contrary, different and often contrasting opinions do persist in interpreting the context of development of some deformation structures and the Tertiary geological history responsible for such a setting; the most recent debates focus on the exhumation mechanisms and their geodynamic context (*Carmignani and Giglia*, 1977; *Carmignani et al.*, 1978; *Carmignani and Giglia*, 1979; *Carmignani and Kligfield*, 1990; *Storti*, 1995; *Cello and Mazzoli*, 1996; *Jolivet et al.*, 1998; *Molli et al.*, 2000).

In the Alpi Apuane metamorphic units two main polyphasic tectono-metamorphic events are recognized: the D1 and D2 events (*Carmignani and Kligfield*, 1990), which are classically regarded as a progressive deformation of the inner Northern Apenninic continental margin during collisional and late to post-collisional processes. During D1, nappe emplacement occurred with development of kilometer scale NE-facing isoclinal folds, SW-NE oriented stretching lineations (L1) and a greenschist regional foliation (S1). In more detail, the D1 event can be subdivided into (1) an "early folding phase" in which recumbent isoclinal folds and an associated flat-lying axial plane foliation are formed, and (2) a later "antiformal stack phase" which produces other isoclinal folds and localized metric to plurimetric scale shear zones with top-to-east/northeast sense of movement. During D2 the previously formed structures were reworked with development of different generations of folds and shear zones, leading to progressive unroofing and exhumation of the metamorphic units toward higher structural levels. Late stages of D2 are associated with brittle structures.

The Alpi Apuane marbles

In the Alpi Apuane region, marbles derive from stratigraphically different levels; the Liassic marbles, however, are the thickest succession and represent the world-famous white variety called "Carrara marble". The "Carrara marble" is extensively used both as building stone and for statuary (this use dates as far back as the Roman age) as well as in rock deformation experiments (*Rutter*, 1972; *Casey et al.*, 1978; *Spiers*, 1979; *Schmid et al.*, 1980, 1987; *Wenk et al.*, 1987; *Fredrich et al.*, 1989; *De Bresser*, 1991; *Rutter*, 1995; *Covey-Crump*, 1997; *Pieri et al.*, 2001b,a) where it is widely used because: a) it is an almost pure calcite marble; b) it shows a nearly homogenous fabric, with no or weak grain-shape or crystallographic preferred orientation; and c) it usually develops a large grain-size.

All the above features can be found in large volumes of marbles cropping out in the Carrara area, i.e. in the northwestern part of the Alpi Apuane region; however, on the scale of the Alpi Apuane region, a variability of microstructure has been described. In local usage the term "Alpi Apuane marbles" indicates all the marble formations cropping out in the whole Alpi Apuane area, while "Carrara marble" stands for Liassic marbles mainly located in the northwestern Alpi Apuane area in the surroundings of the town of Carrara. Carrara marbles are the most intensely quarried marble variety within the entire Alpi Apuane. Due to their economic and cultural importance, Carrara marbles have been the object of geological investigation for a century, with many studies appearing since the sixties.

[Above text modified from *Carmignani et al.* (2004).]

4.6.3 Exercise

Measure several stratigraphic sections to compare to sections measured sections at Cinque Terre.

Chapter 5

Engineering Challenges in Venice

5.1 Introduction

In this section of the GIAC trip we will explore the effort to re-engineer Venice and its surrounding metropolitan area. The Venetian lagoon is faced with numerous large-scale environmental problems due to the interaction of an urban center and delicate wetlands. Land subsidence in Venice, as a result of natural and anthropogenic forcing, is the driving force behind Venice's geological engineering problems. Current estimates of land subsidence in Venice report subsidence rates between 1-5 mm/yr (*ESA*, accessed 2005). The urban center of Venice is directly tied to the estuarine ecosystem which it inhabits. This ecosystem is currently under duress due to anthropogenic forcings such as contamination, sedimentation, and erosion.

We will meet with the Consorzio Venezia Nuova (CVN), the group heading up the lagoon restoration effort, for an introductory meeting and presentation, tour some active engineering solutions, and finally see a scaled model of the lagoon. Throughout these activities, we will gather data and resources on the general hydrostratigraphy of the Venetian lagoon, and the volume of groundwater extraction just south of the lagoon. Using the aquifer parameters and subsidence rates over the last 5 years we will calculate a discharge volume back at home, and compare this to published values. The tour and exercise will expose us to the problems and solutions facing engineers and water managers in Venice.

5.2 Background and Context

The Venetian lagoon, the largest coastal wetland in Italy, is the estuary between the Po river and the north end of the Adriatic Sea. Figures 5.1 and

5.2 are maps of the lagoon and the city of Venice. The average water depth in the lagoon is 1.2 m with a surface area of about 550 km^2, of which just over 400 km^2 is open to the tides of the Adriatic Sea (*Freemantle*, 2000). This complex and fragile environment is directly influenced by the Venice metropolitan area, and in particular, by groundwater and natural gas extraction, land changes due to construction, and pollution from industry.

Venice and the lagoon face three major problems: land subsidence, high tides, and pollution. Venice has a historical subsidence rate of 1 mm/yr. However, groundwater extraction for industrial and agricultural purposes greatly increased the rate, causing up to 23 cm of subsidence from 1950 to 1970 (*Freemantle*, 2000). Subsidence is further compounded by higher tides caused by sea level rise (due to global climate change) and increased hydraulic connectivity between the lagoon and the Adriatic Sea. The increased connectivity is attributed to morphologic changes throughout the lagoon. Flooding and the increased wetting of urban structures is the result, causing rapid deterioration of many Venetian buildings.

Chemical pollution from agriculture and industry has resulted in ecological damage to the lagoon. Nutrient loading, from agricultural runoff along the Po river and raw sewage discharge into the lagoon, causes algal blooms and nitrate contamination. Algal blooms deplete dissolved oxygen concentrations adversely affecting aquatic ecosystems in the lagoon, and alter hydrodynamic circulation in the lagoon (*INCA*, accessed 2005). Heavy metals, dioxins, chlorinated solvents, and petroleum chemicals also pollute the lagoon due to industry in the Venice metropolitan area.

Subsidence, tidal flooding, and pollution are all made worse by the landform changes due to shipping and industry. Dredging of the lagoon for shipping and construction of islands for urban development has altered the hydrology of the lagoon (*Freemantle*, 2000). Islands built from dredged sediment for industrial expansion have reduced the water exchange within the lagoon, retaining pollution. Diversion of natural river paths and the construction of jetties have altered sediment input to the lagoon, causing erosion within the lagoon manifested by the loss of small islands (*CVN*, accessed 2005).

The goal of this section of the GIAC trip is to observe the effects of these various forcings in Venetian lagoon, and be exposed to some of the methods the Italians are using to mitigate these problems.

5.3 Schedule

June 5 Arrive in Venice, explore the main squares, and get a feel for some of the flood damage.

June 6 Spend the day with the CVN

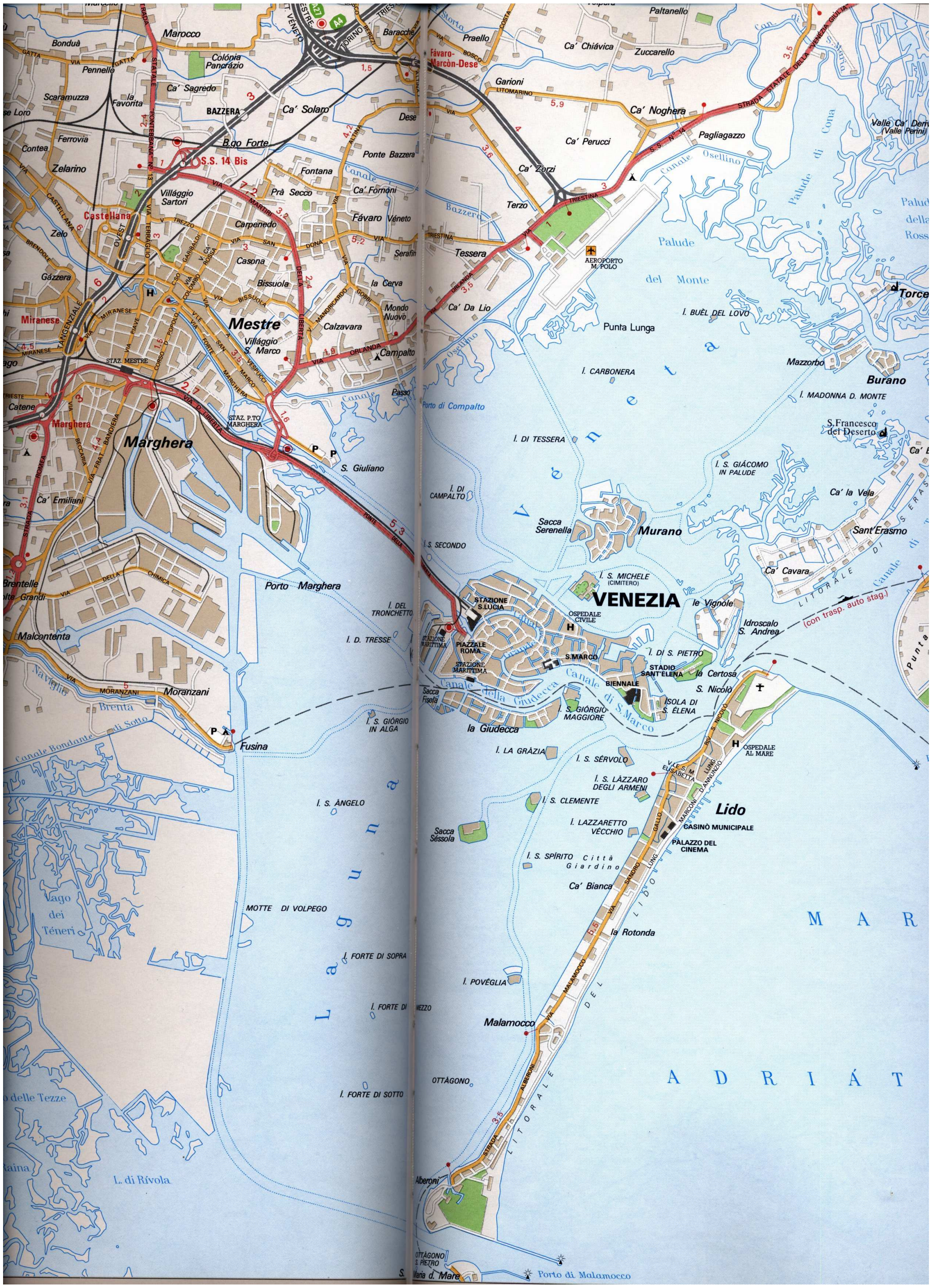


Figure 5.1: Map of the Venetian Lagoon.

Figure 5.2: Map of Venice

9:00 AM **Meet with Consorzio Venezia Nuova**
This is a meeting with the consortium in charge of the restoration of the Venetian lagoon. Discussion of the problems Venice faces and discussion of the current project to restore the lovely lady.

10:30 AM **Begin tour of engineering problems and solutions**
Boat tour to the tidal gates being built to stop high tide flooding in the lagoon. Tour of scale model of lagoon.

5.4 Exercises

During our tours and meeting with the CVN we will glean information on the hydrostratigraphy of Venice lagoon and surrounding area. Parameters we will need are:

1. Overall hydrostratigraphy, including the hydraulic potential, size (extent and thickness), depth, density, and (if available) compressibility of major aquifers in the area

2. Groundwater extraction information, including which aquifers are used for most of the water extraction, and pumping rates of the area south of Chiogga.

3. Subsidence rates can be taken from figure 5.3.

Back at the hotel we will calculate the groundwater extraction rate given the general aquifer parameters, and compare to the published pumping rates.

5.4.1 Calculations

1. What is the vertical stress on the top of the aquifer if the density of water is 1000 kg/m^3 and the porosity (ϕ) is 0.3.

$$\sigma = \rho g h \tag{5.1}$$

2. Using known land subsidence, calculate the change in effective stress on the aquifer each year (assume compressibility of the aquifer to be 2×10^{-7} m^2/kg).

$$\alpha = \frac{\Delta b / b_0}{\Delta \sigma} \tag{5.2}$$

3. What change in head is this each year?

$$\Delta \sigma = \rho g \Delta h \tag{5.3}$$

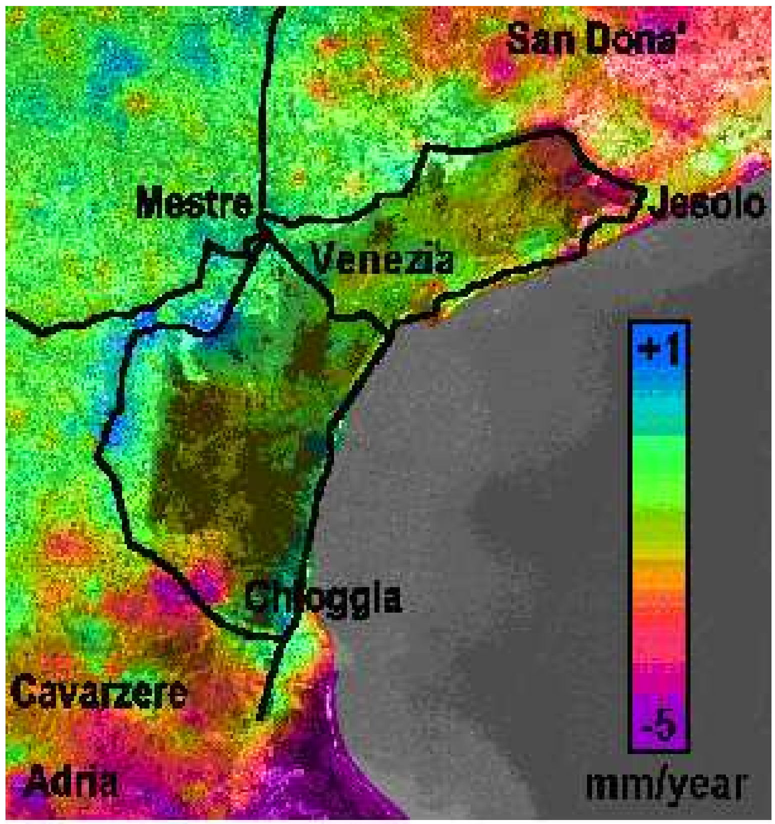


Figure 5.3: Vertical Movement Rates for 1993 to 2000 (*ESA*, accessed 2005).

4. What is the change in porosity (ϕ) each year?

$$\alpha = \frac{\Delta\phi}{\Delta\sigma} \tag{5.4}$$

5. How much water was being pumped out of the aquifer each year during this time?

$$\Delta V_w = V_t \Delta\phi \tag{5.5}$$

Chapter 6

The Alps

6.1 Vaiont Landslide: A Failure of Engineering

6.1.1 Introduction

The Vaiont landslide is located roughly 100 km north of Venice, in the south-eastern portion of the Dolomites. Figure 6.1 shows the local area around the Vaiont reservoir. In 1963, approximately 270 million m^3 of earth detached from the side of Mount Toc and slid into a man-made lake. The lake was formed by a 265 m tall dam, then the second tallest in the world. The displaced water flooded the opposite side of the valley, decimating the town of Casso which sat overlooking the lake. The returning splash rose 100 meters above the dam (for a wave height of 130 m) and rushed down into the villages below. Longarone, Pirago, Villanove, Rivalta, and Fae were flooded, killing over 2,500 people. The dam itself was minimally damaged and still produces hydro-electric power today.

6.1.2 Timeline of the Vaiont Landslide

The Vaiont landslide is an important example of a massive failure in geological engineering and foresight. In the years leading up to the filling of the reservoir a number of studies examined the stability of the overlooking slopes. These studies presented three conclusions:

1. No areas of weakness were identified based on three test borings.

2. Any shear surface (plane) would have a "chairlike" form that would exert a "breaking effect."

3. The overlooking slopes consisted of very firm in-situ rock with high elastic moduli, based on analyses of seismic data. Small slides of loose

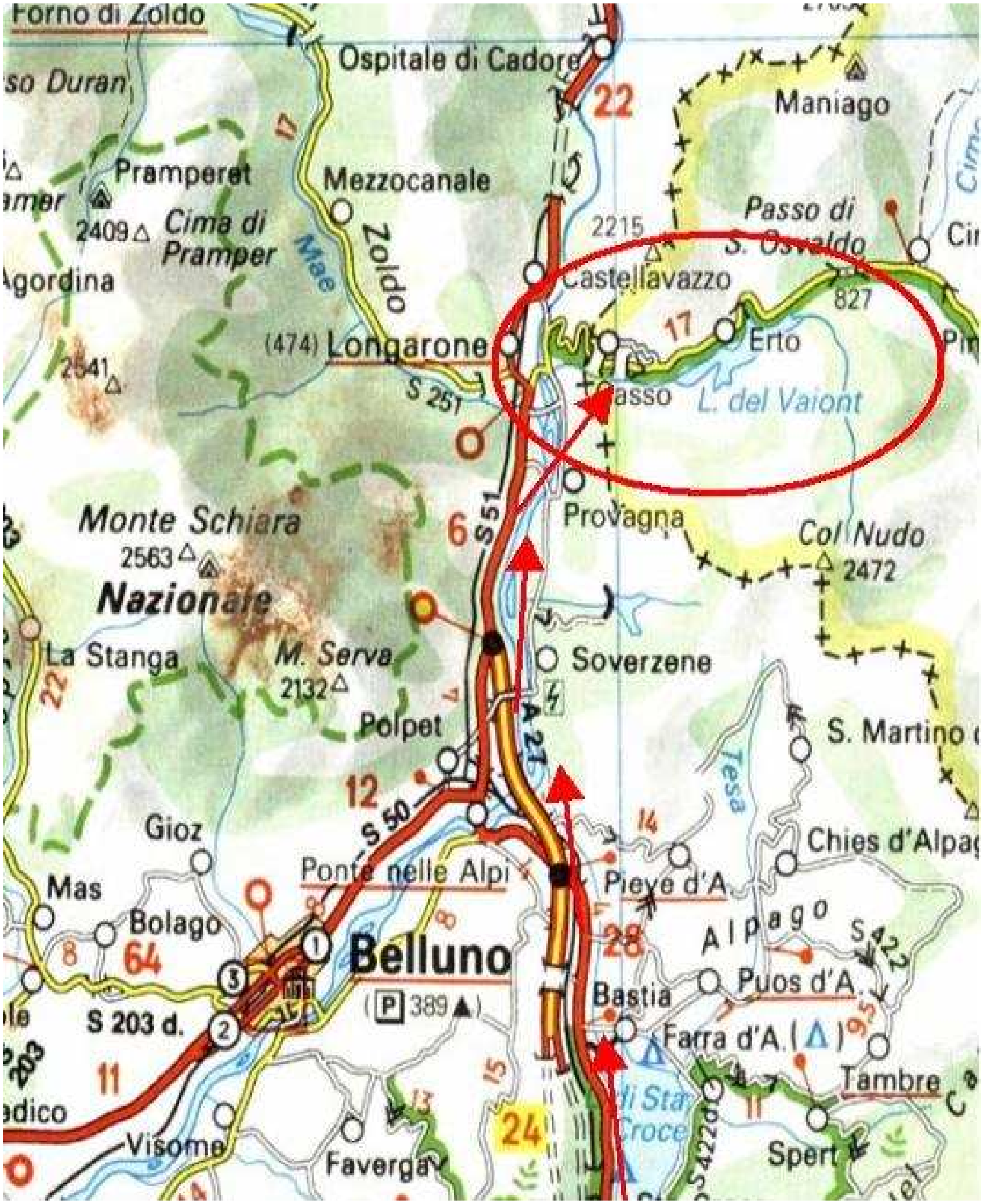


Figure 6.1: Region around Vaiont reservoir.

surface layers were expected, but volume and velocity of the slides would be negligible.

The filling of the reservoir began in February 1960. Even as the reservoir filled, small detachments and slides were observed, consistent with the predictions of the seismic analyses. As the reservoir reached a depth of 170 meters, slope displacement grew to 3.5 cm/day. By November 1960, the reservoir reached a depth of 180 meters. On November 4th, 700 000 m^3 of rock slid into the reservoir. As a precaution, the reservoir was lowered to a depth of 135 meters. After lowering the reservoir level, slope movement slowed to around 1 mm/day. The engineers concluded that the overlooking slopes were inherently unstable, and steps had to be taken to control the situation.

The agreed-upon solution was to build drainage tunnels to limit water infiltration of joints within the slopes. The reservoir was carefully filled to initiate a controlled movement of the slopes, with the rate of movement controlled by the level of the reservoir. Calculations showed that controlling the rate of the slide would avoid spilling over the dam. The reservoir was lowered and raised several times to monitor the effect on the rate of slope movement. By April 1962, engineers felt that they understood the relationship between the reservoir depth and the slope movement rate. After another year of raising and lowering the reservoir level, the reservoir was filled to 235 m. Displacement velocities slowly increased, and by October 1963 movement rates reached 20 cm/day. Late on the night of October 9th, 1963, the catastrophic slide occurred. The limits of the slide, water surge, and flood zones are shown in figure 6.2. Note the large area of the 1963 landslide in comparison to the previous 1960 and ancient landslides.

We might be very lucky to visit the site of Vaiont landslide this year. Starting this summer the dam at Vaiont will be an open-air museum. A footbridge above the broken rim of the dam has been built to allow us to see the result of the catastrophic landslide. The walkway follows the border of the dam, starting at a chapel dedicated to the victims of the landslide. The path continues along a passageway protected by an iron fence, eventually arriving at the section that suffered the full impact of the landslide.

6.1.3 Further Reading

- **Vaiont lecture notes by Dr. Dave Petley**
  http://www.land-man.net/vajont/vajont.html

- **Vaiont: From symbol of tragedy to voyage through time**
  http://turismo.regione.veneto.it/en/ansa/index.php?id=1590

- **Vaiont: A tragedy foretold**
  http://www.italiaplease.com/eng/megazine/giroditalia/2001/10/vajont

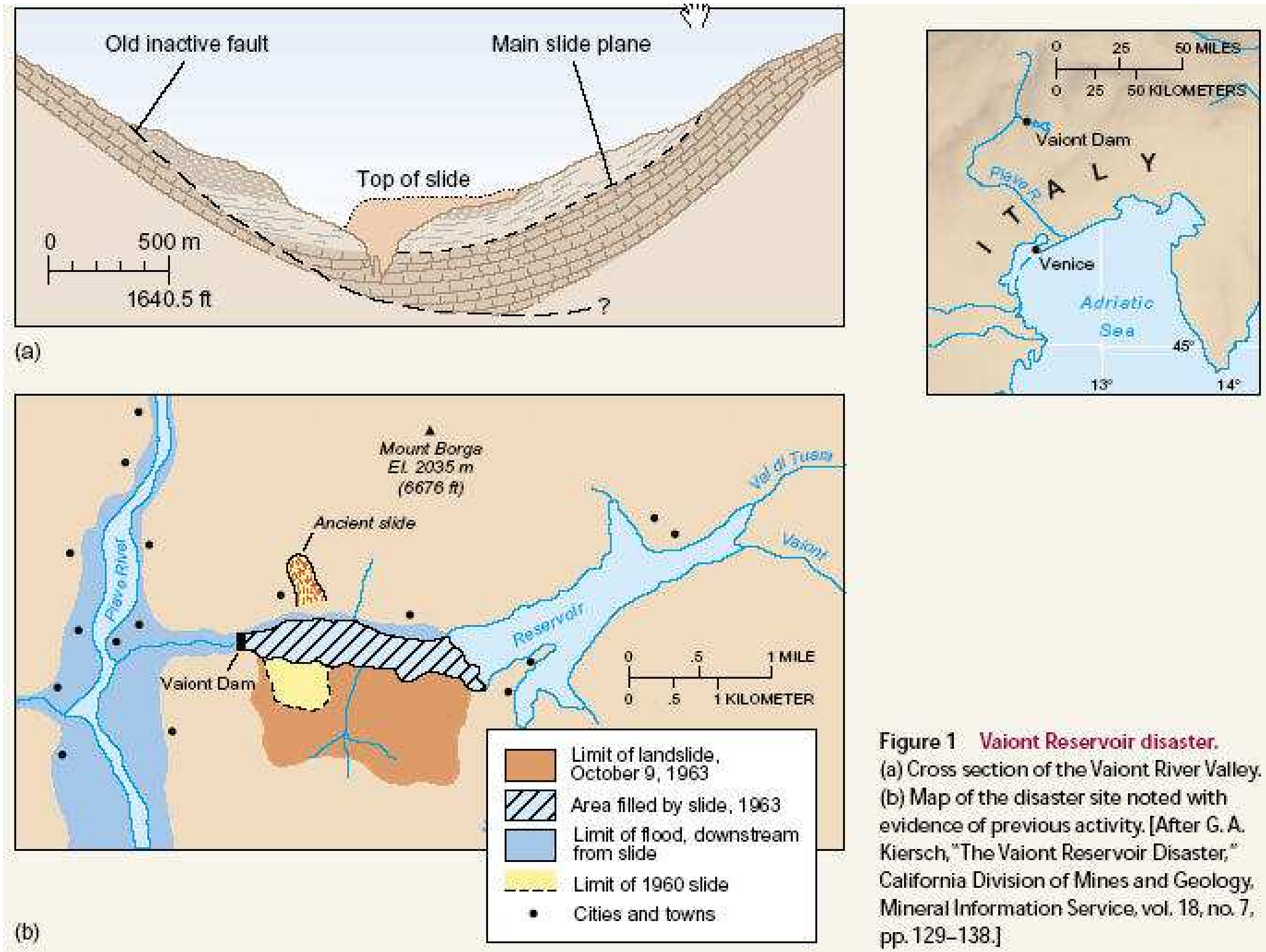


Figure 6.2: Slide, surge, and flood extents of the Vaiont reservoir landslide. Note the five towns completely inside the downstream flood limits.

- **Vaiont Reservoir Landslide Disaster**
http://piru.alexandria.ucsb.edu/collections/geography3b/geosystems/geosystems13-focus.pdf

- **Vaiont: Almost a greek tragedy**
http://www.geocities.com/Athens/Acropolis/2907/vajont.html

6.2 Sella Massif: A Carbonate Platform

6.2.1 Introduction

The Sella Massif is a Tertiary-age, atoll-like, high-relief post-volcanic carbonate platform, with well-preserved depositional geometry. From *Keim and Neri* (2004):

> The whole of the Massif is made up by two superimposed carbonate platforms, forming two steep cliffs, separated by a distinct ledge.... The lower cliff is cut into a Landinian (Middle Triassic) buildup (Sella platform proper), the second one pertains to the Upper Triassic; younger thin deposits occur only at the very summit of the Massif (Piz Boè), showing condensed pelagic limestones (Ammonitico Rosso, Mid-Upper Jurassic) and hemipelagic marls (Puez Marls, Lower Cretaceous). The upper wall [is] made up by the Dolomia Principale–Hauptdolomit consisting of flat lying region-wide peritidal deposits, here about 250 m thick. The peritidal Dolomia Principale is overlain by some tens of meters of Rhaethyan shallow water Dachstein Limestone. The ledge in between the Triassic platform carbonates consists of well-bedded dolomite and marlstone alternations, traditionally referred to as "Raibl Beds". As several litho- and biostratigraphic evidences point out that this correlation is incorrect, they are herein attributed to the Schlernplateau Formation. Towards the centre of the mountain, the thickness of this unit decreases distinctly and is locally reduced to zero.
>
> The lower platform was probably subround in shape, measuring 7–8 km in diameter. The unit consists mainly of clinostratified slope deposits, associated with relatively thin topset beds.... This carbonate body attracted considerable attention in the study of large-scale depositional geometry of isolated platforms ... and is presently referred to a late Landinian time interval. The northern side of the Sella Massif shows a peculiar stratigraphic succession, characterized by the occurrence of a prominent megabreccia body, the "Gardena Megabreccia", up to 200 m thick .... These breccias

are interbedded within the topmost portion of the volcanoclastic basinal sediments....

6.2.2 Field Stops

Figure 6.3 shows the topography of the Sella Massif and local surroundings. The stops are not labelled on the map, but roughly follow the roads that circle the main massif. The list of stops is taken from *Keim and Neri* (2004). More detail on the stop locations can be found in the 32nd IGC field guide, a portion of which is reproduced after the stop listing.

1. **Gardena Pass**
   An example illustrating the various possible explanations for the depositional geometries of these isolated carbonate platforms.

2. **Sella Pass**
   This section shows the Wengen Fm grading into the S. Cassiano Fm and then clinostratified dolomite megabreccia of the "Locomotiva."

3. **Road curve (2200 m) just below Sella Pass**
   An exposed wall of Sass Pordi, with topsets and clinostratifications. Provides insight about the interior of the Sella Massif.

4. **Rif. Monti Pallidi (Pian Schiaveneis; 1850 m)**
   A view of the entire platform along with its' diverging progradation directions.

5. **Pordoi Pass-Sass Pordoi-Piccolo Pordoi**
   A place to observe the post-Cassian Dolomite succession, and walk across the transition from Cassian platform to basin.

6. **Campolongo Pass**
   The succession of outcrops of the eastern flank of the Sella which are used to try to discriminate between multiple hypotheses of the formation of the Sella Massif. See *Keim and Neri* (2004) for a detailed description of the multiple hypotheses, and the evidence visible at this stop.

7. **Road to Gardena Pass**
   A panoramic view of the clinostratifications at the Val de Mesdi, along the NNW-facing flank of the Massif.

6.2.3 32nd IGC Field Trip Guide

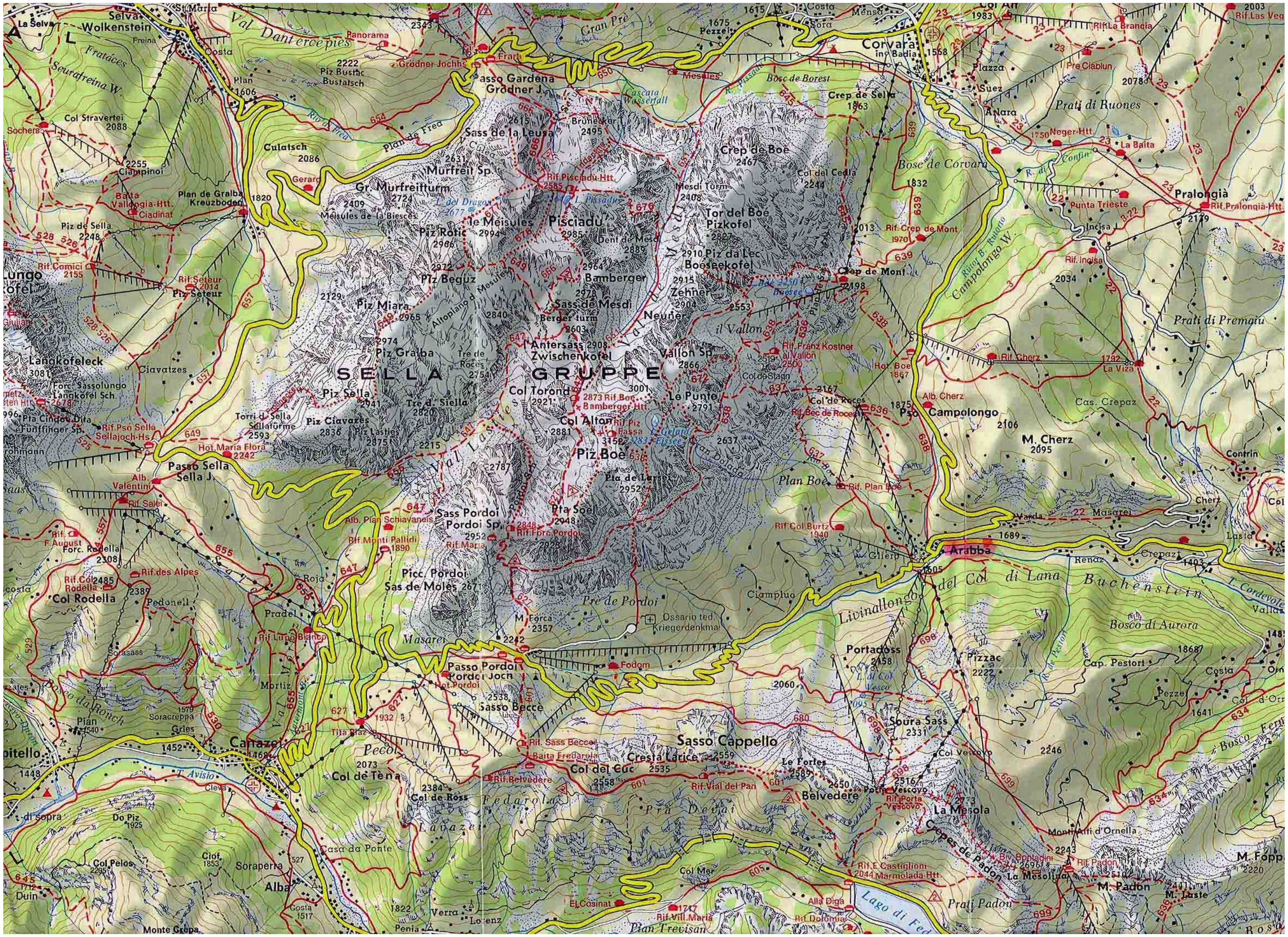


Figure 6.3: Topographic map of the Sella Massif and surroundings.

by different sediment sources, namely detritus from surrounding carbonate platforms, volcanic material as well as test of marine microorganisms and clay. Calciturbidites and volcaniclastics change significantly in thickness and percentage in the Buchenstein basin and were deposited at extremely high sedimentation rates compared to the rates of perennial background sediment. Such changes in sedimentation rates are one of the major obstacles in cyclostratigraphy, because they rule out the simple approach that bed thickness represents time. The separation of these deposits from the background sediment allows the construction of a residual succession, where the effect of changes in sedimentation rate is minimised. This kind of tuning, which is exclusively based on the sedimentology of the formation, was used to detect quasi-periodic signals in the greyscale scan of the core interval between 59 and 45 m ("Bänderkalke" of Buchenstein Fm.). The great advantage of this technique is that one can go back to the core and look at the residual sediment and its bedding patterns. In the figure below a 1 m long interval of the perennial succession used for time series analysis is visually restored and the presumed orbital signals are plotted next to it for comparison. The composite curve of the bandpassed frequency components (ETP, stands for Eccentricity, Tilt, Precession) fits very well to the underlying greyscale scan.

DAY 3

The Sella Platform

L. Keim & C. Neri

Introduction

This day is aimed at observing the well preserved depositional geometry of an atoll-like, high-relief postvolcanic carbonate platform, showing up in the Sella Massif (Figure 4.1). The whole of the Massif is made up by two superimposed carbonate platforms, forming two steep cliffs, separated by a distinct ledge (Figure 4.2). The lower cliff is cut into a Ladinian buildup (Sella Platform proper), the second one pertains to the Upper Triassic; younger thin deposits occur only at the very summit of the Massif (Piz Boè), showing condensed pelagic limestones (Ammonitico Rosso, Mid-Upper Jurassic) and hemipelagic marls (Puez Marls, Lower Cretaceous). The upper wall if made up by the Dolomia Principale – Hauptdolomit consisting of flat lying region-wide peritidal deposits, here about 250 m thick. The peritidal Dolomia Principale is overlain by some tens of meters of Rhaethyan shallow water Dachstein Limestone. The ledge in between the Triassic platform carbonates consists of well-bedded dolomite and marlstone alternations, traditionally referred to as "Raibl Beds". As several litho- and biostratigraphic evidences point out that this correlation is incorrect, they are herein attributed to the Schlernplateau Formation (L. Keim). Towards the centre of the mountain, the thickness of this unit decreases distinctly and is locally reduced to zero.

The lower platform was probably subround in shape, measuring 7-8 km in diameter. This unit consists mainly of clinostratified slope deposits, associated with relatively thin topset beds (Figure 4.3 and 4.4). This carbonate body attracted considerable attention in the study of large-scale depositional geometry of isolated platforms (Leonardi & Rossi, 1957, Bosellini, 1982, 1984, Kenter, 1990, Bosellini & Neri, 1991, Keim & Schlager, 1999, 2001; Keim & Brandner, 2001), and is presently referred to a late Ladinian time interval. The northern side of the Sella Massif shows a peculiar stratigraphic succession, characterised by the occurrence of a prominent megabreccia body, the "Gardena Megabreccia", up to 200 m thick (Bosellini, 1982; Bosellini & Neri, 1991). These breccias are interbedded within the topmost portion of the volcanoclastic basinal sediments (La Valle - Wengen Fm, Figs. 4.2-5).

Remarks on lithostratigraphic terminology

The intricate lithostratigraphic nomenclature of the rock bodies making up the Sella Massif is summarized in Figure 4.2. Different research groups have indicated the same rock-units with different names: thus, the Sella Platform is referred to as Upper Schlern Dolomite by German-speaking authors (including Keim & Brandner, 2001, and L. Keim, this work) and as "Cassian Dolomite" by Italian authors, at least since Assereto et al. (1977); it should be noted, however, that the name "Cassian Dolomit" was firstly proposed by Mojsisovics (1879).

The so-called "Raibl beds" of the Sella, not correlatable to the Raibl Formation in the eastern Dolomites, which is Tuvalian in age and is characterized by red and green shales, whitish dolomicrites, sulphate evaporite, were referred to as "Schlernplateau beds" by Keim & Brandner (2001). This nomenclature is based on the possible correlation of the interval at the Sella with the uppermost part of the Schlernplateau beds cropping out at the top of the Schlern (Sciliar)

Volume n° 5 - from P37 to P54

Volume n° 5 - from P37 to P54

Mountain. In the Sella Massif, the Schlernplateau Fm. was informally subdivided into two laterally interfingering members (Keim & Brandner, 2001): (a) Pordoi Mb: it consists of well-bedded dolomites, interbedded with marlstones; its base is marked by a key-layer consisting of volcanoclastic sandstones, unconformably lying on the top of the "Cassian" Sella Platform and locally infilling open fractures, possibly enlarged by karst; (b) Stevia Mb: it consists mainly of lagoonal mixed terrigenous-carbonate sediments and bivalve coquinas (Myophoria kefersteini kefersteini). The sedimentation pattern of the Schlernplateau Fm. was strongly influenced by synsedimentary tectonics (Keim & Brandner, 2001), resulting in the significant change in thickness shown in Figure 4.2A. Extensional tectonics led to local fissures, block-tilting, graben structures and breccia deposits.

According to L. Keim (this work) the formational name "Schlernplateau" has to be extended to the so-called "Dürrenstein Dolomite" sensu Bosellini (1984), cropping out on eastern flank of the Sella Massif (Campolongo Pass) and interpreted by Bosellini & Neri (1991) as an aggrading carbonate body nucleating from the basin floor and onlapping the former Cassian platform slope (Figure 4.2C). A comparison between Figures 4.2A and 4.2C clearly shows that, also in this case, the difference in nomenclature reflects two distincly differing stratigraphic interpretations, that will be discussed at Stop 6 (Campolongo Pass).

Biostratigraphy and age

The available biostratigraphic data derive from several basinal sections outcropping around the

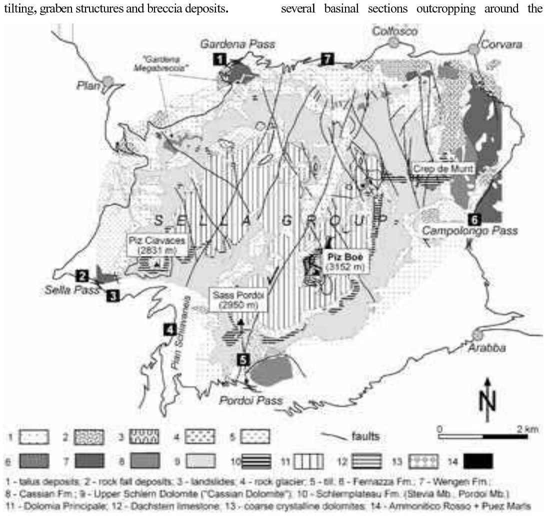


Figure 4.1 - Schematic geological map of the Sella Group, with localisation of the trip stops.

Figure 6.4: Excerpt from 32^{nd} IGC field guide

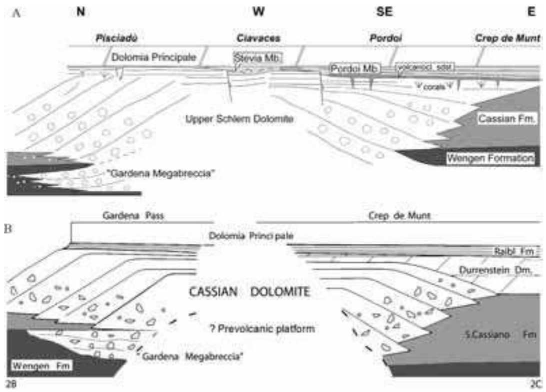


Figure 4.2 - Two alternative interpretation of the Sella Platform stratigraphy, see main text for discussion.
The thickness of the Sella Platform is at least 500 m.

Sella Massif and from the sediments immediately overlying the platform top at the Ciavaces Plateau. The ammonoid faunae of the Wengen and S. Cassiano sections around the Sella Massif (Reithofer, 1928; Mietto & Manfrin,1995; Baracca, 1996) clearly indicate an upper Ladinian Age (*Regoledenus* Zone). The S. Cassiano Fm section outcropping above the "Gardena Megabreccia" (Col de Frea) was assigned by Mietto & Manfrin (1995b) to the Daxatina cf. *canadensis* Subzone (corresponding to upper part of the *Regoledanus* Zone of Krystyn, in Zapfe, 1983). Recently, the genus Daxatina was proposed as the marker for the Carnian Stage base (Mietto & Manfrin, 1995 a,b; Broglio Loriga et al., 1999), but, since any official decision by the Subcommission on Triassic Stratigraphy is lacking, we still refer the Sella Platform to the Upper Ladinian, according to Krystyn (in Zapfe, 1984).

Conodonts form the Wengen and S.Cassiano Fms (Mastandrea et al., 1997, 1998) at the Gardena Pass and Sella Pass sections also clearly indicate an Upper Ladinian age. The faunae are dominated by genus *Budurovignathus* and belong to the *diebeli* Assemblage Zone sensu Krystyn (1983) and Gallet et al. (1998), corresponding to the standard *Regoledanus* Zone (Upper Ladinian). The age of the Schlernplateau Fm is inferred on the basis of the frequent occurrence of the bivalve *Myophoria kefersteini kefersteini* (Ciavaces plateau, Keim & Brandner, 2001). According to Urlichs & Tichy (2000) this taxon is Early Carnian in age (Aon Zone, base of Julian 1 of Krystyn, 1979).

Tectonics

Alpine compressional deformation is often comparatively mild in the Sella Massif, mainly recorded by small offset faulting (Mollema & Antonellini, 1999), or gentle folding (i.e. the Plan Anticline, the southern flank of which form the N-side of Sella, see Figure 4.5). A marked exception is represented by the eastern flank, involved in important overthrusting and dissected by several, nearly N-S trending, high-angle faults (Doglioni, 1985,1992, Keim & Brandner, 2001). The uppermost portion of the massif is caracterized by some klippen structures known as "summit-thrusts" (German: "*Gipfelfaltungen*"; Italian: "*sovrascorrimenti di*

Figure 4.3 - View of the northern side of the Sella Group. The lower wall corresponds to the "Gardena Megabreccia" at the Gardena Pass (Groedner Pass – Frara), note the wedging out of the carbonate tongues within the uppermost portion of the basinal La Valle – Wengen Formation; the upper wall is cut into the clinostratified Sella Platform slope; in the topmost portion a thin level of horizontally stratified platform top beds is locally visible.

vetta") and spectacularly exposed at Piz Boè. As a result, while the primary geometric-stratigraphic relationships between Cassian basin and platform deposits are quite well preserved throughout most of the Sella Massif, the geometry at the eastern side of the Sella are not entirely settled and are still a matter of debate.

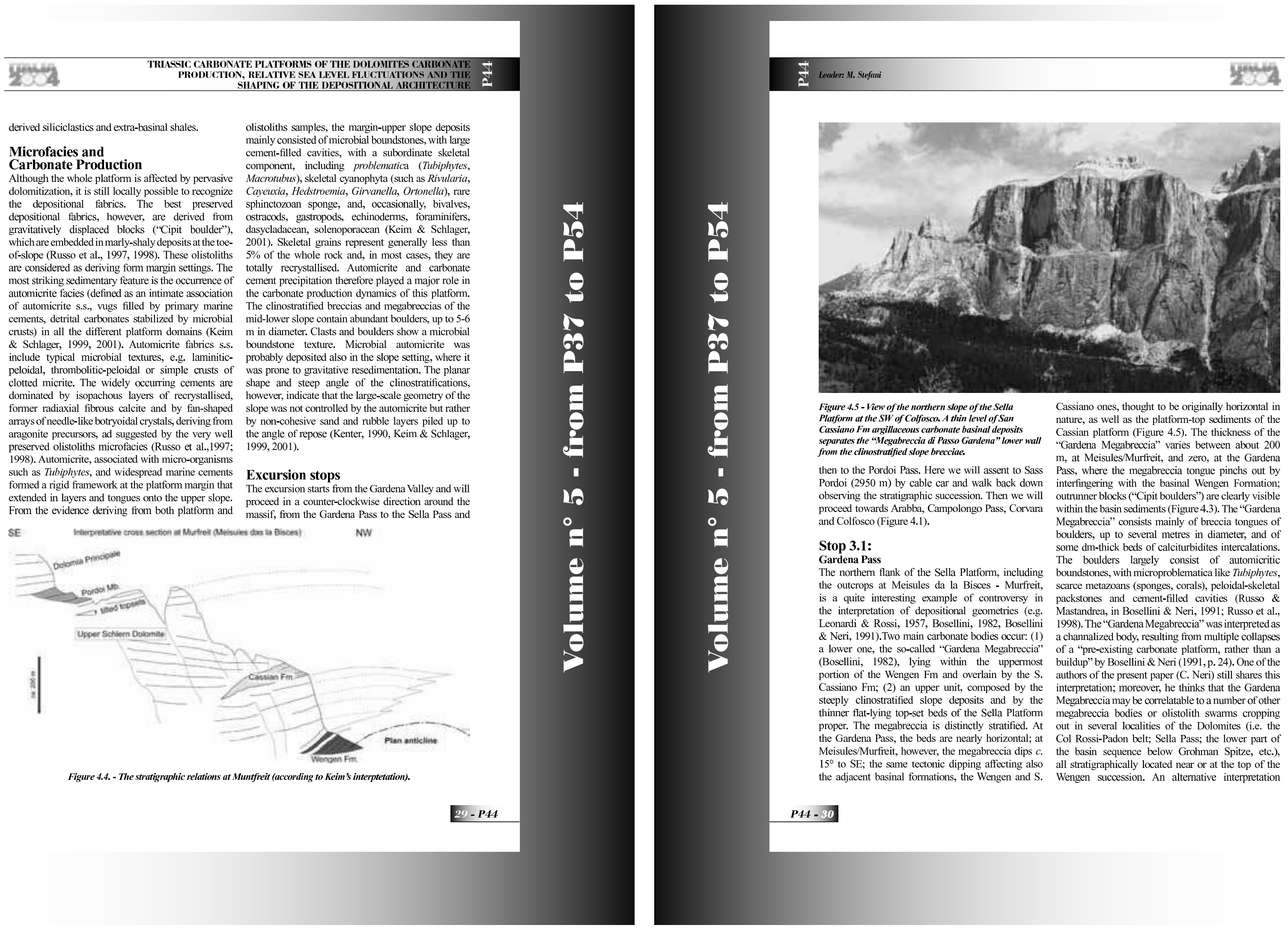
Geometry and sedimentology of the Sella platform

The steep (30-35°) clinoforms of the Sella show radial progradation and interfinger on all sides with the basinal sediments of the S. Cassiano Formation. Judging by the height of the clinoforms, the platform reaches a maximum thickness of 600 m; the inner core, however is not outcropping. The shallow water topset layers show even tabular bedding, 0.1-1 m thick. Sedimentary structures are rarely preserved, being represented by occasional cross-bedding and by meter-size tepees. At Pisciadù, within the topset beds, nice *Thecosmilia* like coral colonies have been found in growth position. The margin between platform-top and slope deposits is quite narrow, a few tens of meters wide at the most. At upper slope settings, the shape of the clinostratifications is often planar, although it exhibits erosional scars (Kenter, 1990). On the lower slope, the shape of clinostratifications is distinctly concave, as the dip gradually flattens out towards the basin floor, particularly where the base of slope is characterized by a climbing progradation (e.g., Sella and Pordoi passes). In the Val di Mesdì area, where tabular progradation occurs over a thin wedge of basin deposits, the clinostratifications show an oblique parallel geometry (Bosellini & Neri, 1991). Intensive downslope transport is recorded by debris aprons at the toe-of-slope; these aprons, however, are rather narrow (a few hundred metres width) and the slope carbonates pass rapidly into basinal marls and shales, as for instance visible at the Gardena Pass, at the "Locomotiva" (Sella Pass), and in Val de Mesdì. The aprons consist of calciturbidites, debrites and swarms of meter-size boulders (Bosellini & Neri, 1991). In addition, the basins were fed with volcano-

Volume n° 5 - from P37 to P54

Volume n° 5 - from P37 to P54

Figure 6.5: Excerpt from 32nd IGC field guide



TRIASSIC CARBONATE PLATFORMS OF THE DOLOMITES CARBONATE PRODUCTION, RELATIVE SEA LEVEL FLUCTUATIONS AND THE SHAPING OF THE DEPOSITIONAL ARCHITECTURE P44

derived siliciclastics and extra-basinal shales.

Microfacies and Carbonate Production

Although the whole platform is affected by pervasive dolomitization, it is still locally possible to recognize the depositional fabrics. The best preserved depositional fabrics, however, are derived from gravitatively displaced blocks ("Cipit boulder"), which are embedded in marly-shaly deposits at the toe-of-slope (Russo et al., 1997, 1998). These olistoliths are considered as deriving form margin settings. The most striking sedimentary feature is the occurrence of automicrite facies (defined as an intimate association of automicrite s.s., vugs filled by primary marine cements, detrital carbonates stabilized by microbial crusts) in all the different platform domains (Keim & Schlager, 1999, 2001). Automicrite fabrics s.s. include typical microbial textures, e.g. laminitic-peloidal, thrombolitic-peloidal or simple crusts of clotted micrite. The widely occurring cements are dominated by isopachous layers of recrystallised, former radiaxial fibrous calcite and by fan-shaped arrays of needle-like botryoidal crystals, deriving from aragonite precursors, ad suggested by the very well preserved olistoliths microfacies (Russo et al.,1997; 1998). Automicrite, associated with micro-organisms such as *Tubiphytes*, and widespread marine cements formed a rigid framework at the platform margin that extended in layers and tongues onto the upper slope. From the evidence deriving from both platform and olistoliths samples, the margin-upper slope deposits mainly consisted of microbial boundstones, with large cement-filled cavities, with a subordinate skeletal component, including *problematica* (*Tubiphytes*, *Macrotubus*), skeletal cyanophyta (such as *Rivularia*, *Cayeuxia*, *Hedstroemia*, *Girvanella*, *Ortonella*), rare sphinctozoan sponge, and, occasionally, bivalves, ostracods, gastropods, echinoderms, foraminifers, dasycladacean, solenoporacean (Keim & Schlager, 2001). Skeletal grains represent generally less than 5% of the whole rock and, in most cases, they are totally recrystallised. Automicrite and carbonate cement precipitation therefore played a major role in the carbonate production dynamics of this platform. The clinostratified breccias and megabreccias of the mid-lower slope contain abundant boulders, up to 5-6 m in diameter. Clasts and boulders show a microbial boundstone texture. Microbial automicrite was probably deposited also in the slope setting, where it was prone to gravitative resedimentation. The planar shape and steep angle of the clinostratifications, however, indicate that the large-scale geometry of the slope was not controlled by the automicrite but rather by non-cohesive sand and rubble layers piled up to the angle of repose (Kenter, 1990, Keim & Schlager, 1999, 2001).

Excursion stops

The excursion starts from the Gardena Valley and will proceed in a counter-clockwise direction around the massif, from the Gardena Pass to the Sella Pass and

Figure 4.4. - The stratigraphic relations at Muntfreit (according to Keim's interptetation).

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Volume n° 5 - from P37 to P54

P44 Leader: M. Stefani

Figure 4.5 - View of the northern slope of the Sella Platform at the SW of Colfosco. A thin level of San Cassiano Fm argillaceous carbonate basinal deposits separates the "Megabreccia di Passo Gardena" lower wall from the clinostratified slope brecciae.

then to the Pordoi Pass. Here we will assent to Sass Pordoi (2950 m) by cable car and walk back down observing the stratigraphic succession. Then we will proceed towards Arabba, Campolongo Pass, Corvara and Colfosco (Figure 4.1).

Stop 3.1:
Gardena Pass

The northern flank of the Sella Platform, including the outcrops at Meisules da la Bisces - Murfreit, is a quite interesting example of controversy in the interpretation of depositional geometries (e.g. Leonardi & Rossi, 1957, Bosellini, 1982, Bosellini & Neri, 1991).Two main carbonate bodies occur: (1) a lower one, the so-called "Gardena Megabreccia" (Bosellini, 1982), lying within the uppermost portion of the Wengen Fm and overlain by the S. Cassiano Fm; (2) an upper unit, composed by the steeply clinostratified slope deposits and by the thinner flat-lying top-set beds of the Sella Platform proper. The megabreccia is distinctly stratified. At the Gardena Pass, the beds are nearly horizontal; at Meisules/Murfreit, however, the megabreccia dips *c.* 15° to SE; the same tectonic dipping affecting also the adjacent basinal formations, the Wengen and S. Cassiano ones, thought to be originally horizontal in nature, as well as the platform-top sediments of the Cassian platform (Figure 4.5). The thickness of the "Gardena Megabreccia" varies between about 200 m, at Meisules/Murfreit, and zero, at the Gardena Pass, where the megabreccia tongue pinchs out by interfingering with the basinal Wengen Formation; outrunner blocks ("Cipit boulders") are clearly visible within the basin sediments (Figure 4.3). The "Gardena Megabreccia" consists mainly of breccia tongues of boulders, up to several metres in diameter, and of some dm-thick beds of calciturbidites intercalations. The boulders largely consist of automicritic boundstones, with microproblematica like *Tubiphytes*, scarce metazoans (sponges, corals), peloidal-skeletal packstones and cement-filled cavities (Russo & Mastandrea, in Bosellini & Neri, 1991; Russo et al., 1998). The "Gardena Megabreccia" was interpreted as a channalized body, resulting from multiple collapses of a "pre-existing carbonate platform, rather than a buildup" by Bosellini & Neri (1991, p. 24). One of the authors of the present paper (C. Neri) still shares this interpretation; moreover, he thinks that the Gardena Megabreccia may be correlatable to a number of other megabreccia bodies or olistolith swarms cropping out in several localities of the Dolomites (i.e. the Col Rossi-Padon belt; Sella Pass; the lower part of the basin sequence below Grohman Spitze, etc.), all stratigraphically located near or at the top of the Wengen succession. An alternative interpretation

P44 - 30

Figure 6.6: Excerpt from 32nd IGC field guide

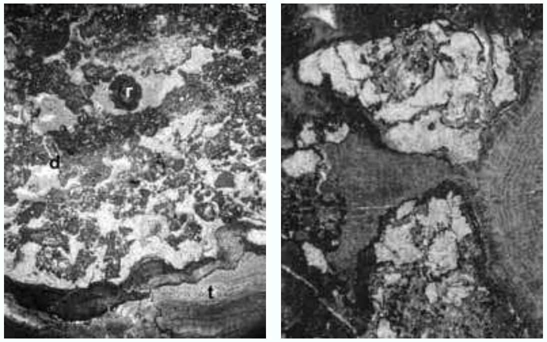


Figure 4.6 - LEFT - Automicrite and skeletal detritus from topset beds. The main part of the picture consists of a network of automicrite with pellet structure. Note occasional lithoclasts, fragments of red algae (r), dasycladacean thalli (d) and cement filling irregular vugs. The fibrous cement layer at the tepee-level (t) is partially dissolved. (Val de Mesdì, width of picture = 2 cm). (After Keim & Schlager, 1999); RIGHT - Thin section photomicrograph of automicrite facies on the marginupper slope, composed of dark crusts of peloidal clots, limpid botryoidal cement, numerous generations of fibrous cement as well as internal sediment. Automicrite forms constructional cavities and gravity-defying fabrics indicating that automicrite lithified almost immediately upon formation. (Val Lasties, width of picture = 3 cm). (After Keim & Schlager, 2001).

of the Northern Sella stratigraphy proposed by L. Keim (Keim & Schlager, 2001) is essentially a step back to the model of Leonardi & Rossi (1957), who assumed a lateral interfingering between the "Gardena Megabreccia" and the basinal sediments. In this interpretation, the strong thickness variation (0-200 m) of the megabreccia body is related to the oblique erosive cut of the proximal-distal parts of these deposits and the inclination of the megabreccia bedding (flat-lying, SEdip) is though to be the result of Alpine tectonic deformation (Plan anticline).

Stop 3.2:
Sella Pass
The section at the Sella Pass shows the Wengen Fm basinal succession grading up-section into the S.Cassiano Fm and eventually into W-dipping clinostratified dolomite megabreccia of the so called "Locomotiva". The section consists mainly of marlstones, siltstones, volcanoclastic sandstones and conglomerates, skeletal and lithoclastic calciturbidites and carbonate breccias. The section top shows the interfingering of basinal beds and clinostratified Cassian Platform slope. These clinostratifications are distinctly flattening out basinwards, since their dip angle decreases from about 30° in Val Lasties to 20° at Sella Towers (Kenter, 1990). The topsets are here only 10-20 m thick; the transition zone to the steeply dipping clinoforms is rather massive and apparently structureless.

Stop 3.3:
Road curve (2200 m) just below the Sella Pass
This stop offers a panoramic view of the WNW-exposed wall of Sass Pordoi with its topsets and clinostratifications and provides some insights into the interior of the Sella Platform, outcropping in the Val Lasties. The thinning out of the recessively weathered Schlernplateau Fm (Pordoi Mb = Raibl Fm *Auctorum*) above the platform top can also be observed.

Volume n° 5 - from P37 to P54

Volume n° 5 - from P37 to P54

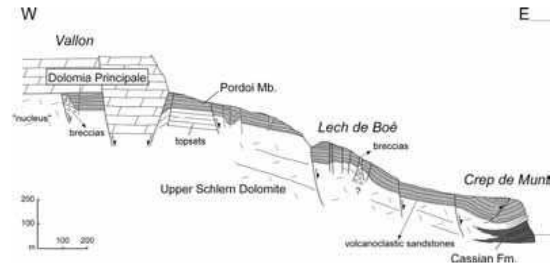


Figure 4.7 - Cross section at the Sella eastern side (modified after Keim & Brandner, 2001)

Stop 3.4:
Rif. Monti Pallidi (Pian Schiaveneis; 1850 m)
From this topographic view point, the full platform dimension and its diverging progradation directions (W-dipping clinoforms at Pic Ciavaces and S-dipping clinoforms below Piccolo Pordoi) can be well observed.

Stop 3.5:
Pordoi Pass-Sass Pordoi-Piccolo Pordoi
The stop is aimed at the observation of the post-Cassian Dolomite succession and at a cross-walking of the Cassian platform-to-basin transition. The trail from Sass Pordoi to Piccolo Pordoi (2,692) crosses the Norian Dolomia Principale cyclic peritidal succession. Below, a monotonous alternation of light and greenish coloured dolostones with burrows, fenestrae and desiccation cracks, interbedded with minor marls, crops out. At the base of this unit (Piccolo Pordoi) the Cassian platform top is sharply overlain by 2 m thick, cross-bedded greenish sandstones, mainly consisting of volcanic lithoclasts, quartz, detrital feldspars, minor carbonate grains (ooids, lithoclasts, echinoderm fragments), scarce volcanic glass, glauconite and opaque minerals (Keim & Brandner, 2001). The sandstones occur also as fissures-fillings within the Upper Schlern Dolomite. The fissures are some dm's wide, taper downward to a depth of several meters to tens of meters. These structures may be interpreted as karst dikes or dissolution-enlarged fractures develloped during subaerial exposure of the platform (Keim & Brandner, 2001).

Stop 3.6:
Campolongo Pass
The successions outcropping on the eastern flank of the Sella, from Crep de Munt to Vallon (Sasso delle Dieci), has led to many different stratigraphic interpretations (Mojsisovics, 1879, Bosellini & Neri, 1991, Doglioni, 1992; Keim & Brandner, 2001). Bosellini and Neri (1991) suggested an onlap geometry of the "Dürrenstein Dolomite" onto Cassian Dolomite clinofroms, whereas Doglioni (1992) assumed a thrust plane between the two formations. In both interpretations, however, the Dürrenstein Dolomite was interpreted as an aggrading sedimentary body, nucleating from the basin floor as a response to basin shallowing due to sedimentary infilling and, possibly, to a sea-level drop (Bosellini, 1984). The result is the deposition of an even-bedded carbonate body infilling the residual basins and onlapping the slopes of former Cassian platforms (Figure 4.2C). The peculiarity of the interpretation of Doglioni (1992) is that he puts in evidence that the original onlap geometry has been modified by compressional stress, resulting in moderate thrusting of the Dürrenstein Dolomite over a ramp represented by the inherited Cassian slope. An alternative interpretation has been proposed by Keim & Brandner (2001) and is here presented by L. Keim, following a model formerly suggested by Schlager et al. (1991) for the Picco di Vallandro (Dürrenstein) Cassian platform. This model suggests a progressive infilling shallowing of the Cassian basins, matched with a dip-angle reduction of the platform-

Figure 6.7: Excerpt from 32nd IGC field guide

slope, climaxing into a lateral palaeogeographic homogenisation into a gently deepping ramp-like, shallow water depositional system. The uppermost part of the S.Cassiano Fm exposed at Crep de Munt, including hummocky-cross-bedded oolitic grainstone and peloidal packstone, has been interpreted by various authors as a response to the shallowing of the Cassian basin (Bosellini & Neri, 1991, Keim & Brandner, 2001). According to Keim & Brandner (2001), the last tongues of the Cassian platform overlaid these deposits with a very low depositional angle, probably <2°. L. Keim (this work) concludes that all deep basins around the Sella atoll were filled up at the ending of the Cassian Dolomite deposition. Based on this assumption, the Pordoi Mb (Dürrenstein Dolomite of Bosellini & Neri , 1991, and Keim & Brandner, 2001) does not form an onlap on a steep palaeo-slope surface, but was rather deposited on a very gently dipping slope (Keim & Brandner, 2001). The postulated filling up of the former relief between platform top and the S. Cassian basin is supported by the presence of volcanoclastic sandstones, which can be traced with a rather constant thickness from the former basin towards the platform top (Figs. 2A, 7). On a steeply flanked platform, the input of coarse volcanoclastic material would not have reached the platform top. At Crep de Munt, the Pordoi Mb can be subdivided into a lower subtidal and an upper peritidal unit. The subtidal unit (c. 50-60 m thick) wedges out towards the platform top, where it is reduced to a few meters. In the opinion of L. Keim (this work) this reduction in thickness could be explained by the gently east-dipping, low-gradient palaeo-relief of the underlying Cassian slope or by newly created accommodation space related to synsedimentary extensional tectonics. In the interpretation of Bosellini & Neri (1991) this is, on the contrary, a clear evidence of the onlap relationships on an inherited slope.

Stop 3.7:

Road to Gardena Pass

The last stop provides us with a panoramic view of the spectacularly exposed clinostratifications at the Val de Mesdì, along the NNW-facing flank of the Sella.

Acknowledgements

We gratefully acknowledge R. Brandner (Innsbruck), P. Gianolla (Ferrara), A. Mastandrea and F. Russo (Cosenza) for stimulating discussions. Special thanks go to A. Gruber and H. Gruber (Innsbruck) for substantial help during fieldwork, and to M.Stefani (Ferrara) for scientifific discussion and extended reviewing.

DAY 4

The pre-volcanic Cernera and the Post-Volcanic Nuvolau and Lastoi de Formin Platforms

A. Riva, P.Gianolla, M. Stefani

Introduction

This day will offer a wealth of opportunity to examine pre- and post-volcanic carbonate platform systems, developed within the Eastern/Western Dolomites hinge belt. As discussed in the introduction (cf. Figure 1.6), the less subsiding western region is characterised by upper Anisian carbonates almost directly lying on a single sequence bounding unconformity, deeply cut into the Lower Triassic and older units; these carbonates were followed by thick Anisian-Ladinian platforms (Sciliar Fm), aggrading and widely prograding over thin basinal limestones (Livinallongo Fm), until the onset of the volcanic event; the Upper Triassic is thin and gap-prone. The eastern and northern area is on the contrary typifies by various generations of Anisian carbonate platforms, separated by gently eroded boundaries, followed by long-lasting terrigenously influenced basinal deposits; the Ladinian volcanism did not directly affect the area and the Upper Triassic successions are quite thick and more continuous in nature. In the hinge belt, several brittle (trans)-tensive Middle Triassic structures developed, to be variously reactivated by the Alpine compression. The visited area therefore offers:

(i) The good preservation of three superposed Anisian platform generations and depositional sequences.

(ii) The record of an isolated carbonate pinnacle evolution (Cernera Platform), during younger Anisian and earliest Ladinian times "bravely fighting for survival" against fast subsidence, but eventually giving up to retrogradation, deepening and final drowning into aphotic conditions, where a pelagic shroud of limestones slowly accumulated. Thick terrigenous and volcanoclastic successions then onlapped the former platform slope.

(iii) Spectacular post-volcanic platforms (Gusela del Nuvolau and Lastoi de Formìn), conquering the area again during the Carnian Time, when fine grained calcarenitic slopes, significantly less inclined than the pre-volcanic ones, prograded onto the San Cassiano basinal Fm, eventually filling up all the available accommodation space.

(iv) A nice example of a potential hydrocarbon

Figure 6.8: Excerpt from 32nd IGC field guide

6.3 Ivrea-Verbano: Journey to the Bottom

6.3.1 Introduction

The Ivrea-Verbano Zone of northwest Italy preserves one of the finest examples of the interaction of mantle-derived melts with continental crust. This area is widely thought to represent a section through the lower continental crust uplifted during the Alpine orogeny, based primarily on the presence of lenses of mantle peridotite (*Schmid*, 1968; *Berckhemer*, 1969; *Fountain*, 1976). Of particular interest is evidence for underplating as the driving force for granulite facies metamorphism and depletion of lower crustal rocks by removal of a granite melt. The Ivrea-Verbano Zone is subdivided into the Kinzigite Formation, consisting of amphibolite to granulite facies metasedimentary rocks, and the Basic Formation, consisting of lenses of mantle peridotite in a mafic complex. However, the interpretation of a mantle-crust boundary within the Zone is not universally accepted; an alternate hypothesis for the mantle peridotite emplacement is assembly within an accretionary wedge (*Quick et al.*, 1995). Nevertheless, it is widely accepted that the Ivrea-Verbano Zone represents a unique view of deep continental crust regardless of the presence of a mantle-crust interface. Maps for this series of stops are mostly found in the reference map section (chapter 2). Of particular use are the Monte Rosa topographic map (figure 2.5) and tectonic map of northwestern Italy (figure 2.10). The geologic map of the Strona Valley (figure 6.9) shows the continuation of the Ivrea-Verbano Zone to the south of the field stops, and can be useful for getting a large-scale picture of the area.

6.3.2 Questions:

1. What are the dynamics of partial melting in the lower crust, and what is the rheological response of the lower crust to partial melting and melt transfer?

2. What is the role of crust-mantle interaction, and what geochemical signatures can be used to identify crustal addition, removal, or differentiation during active deformation?

3. What are the specific links between the petrologic and structural, and the kinematic and dynamic expressions of melt migration?

4. What are the sources of heat to drive these chemical and kinematic processes?

5. What do we really need to know to test models of melt segregation and transfer in the continental crust?

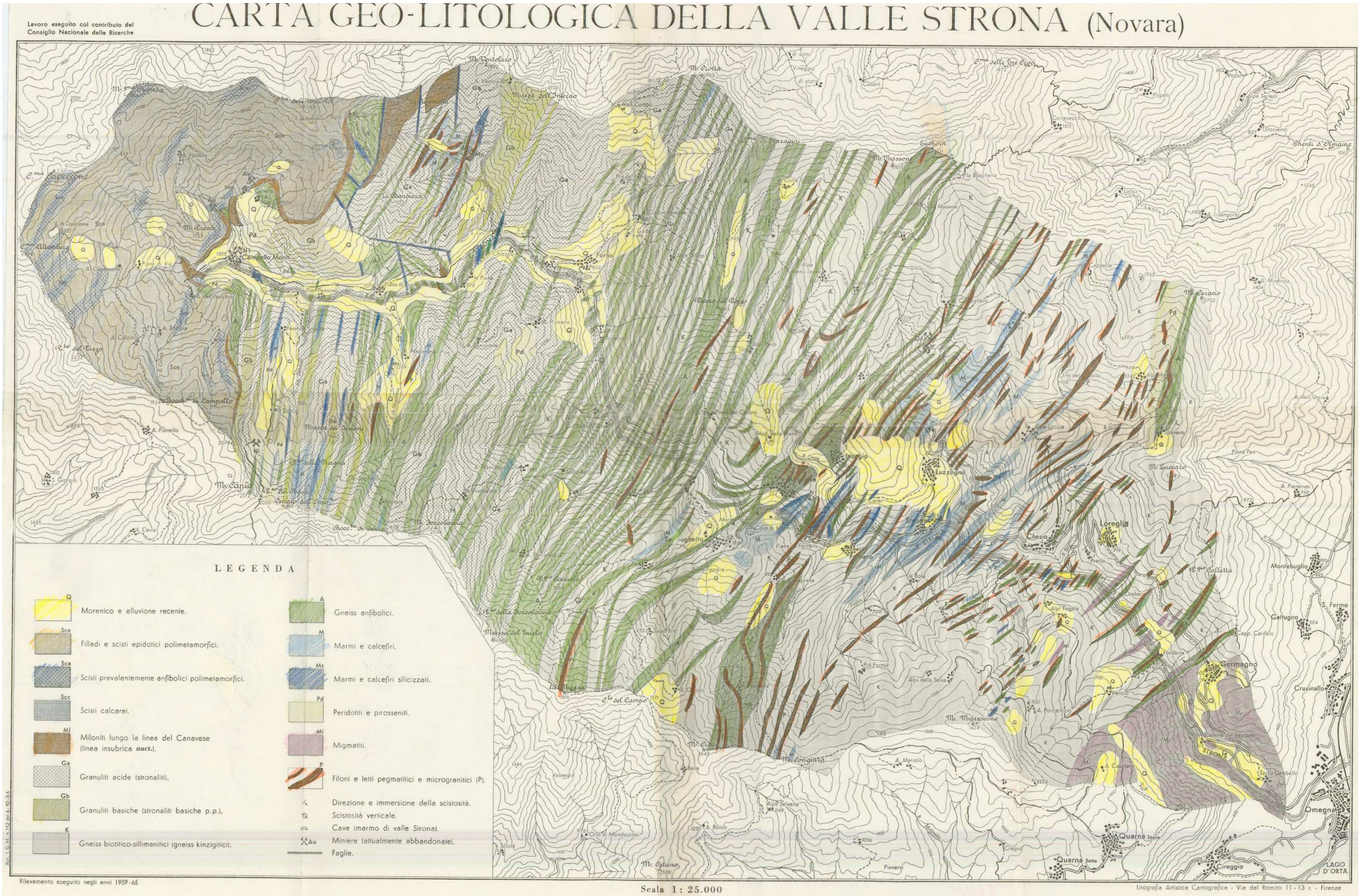


Figure 6.9: Geology of the Strona Valley, at 1:25 000 scale.

6. Does the Ivrea-Verbano zone truly preserve a mantle-crust transition or was mantle peridotite emplaced through a different process?

6.3.3 Exercises:

The Ivrea-Verbano zone presents a unique opportunity to observe the lower crust and possibly a crust/mantle transition in the field. However, due to the large size of the area and the limited time allotted for investigation, exercises will be limited to observations at a series of planned stops. These field based observations will give an opportunity to address several questions regarding the origin of these rocks and the processes involved in their genesis. A simplified geologic map of the area, along with the stop locations, is shown in figure 6.10.

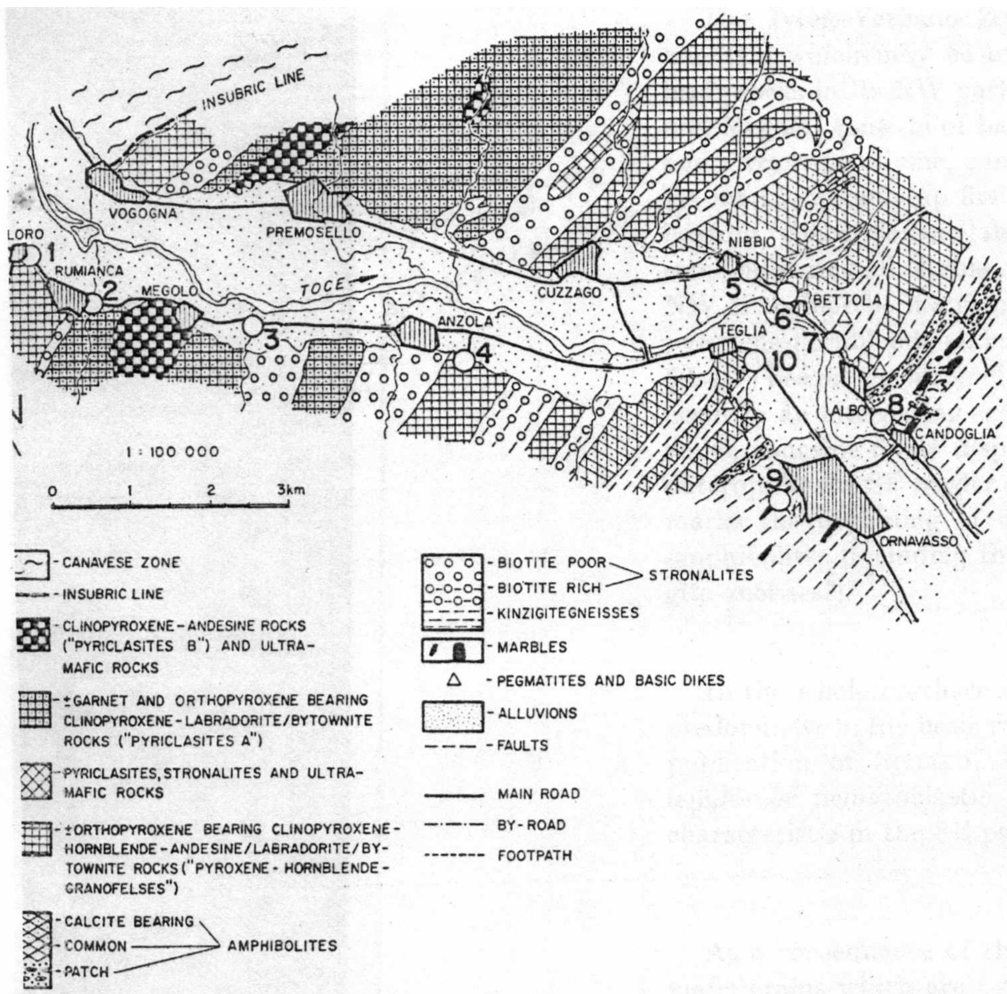
(From *Schmid* (1968))

1. **Chapel of Loro**
   The SE part of the chapel rests on clinopyroxene-bearing hornblende plagioclase rocks (hornblende granofelses), the NW part on mylonites of the Insubric Line. Above the houses of Loro, SW of the Chapel: sericite-chlorite and carbonate schists of the Canavese Zone, containing inclusions of pyroxene-hornblende granofelses. Walking from the Chapel some hundred meters in direction SE (along the border of the Valle d'Ossola), the Alpine retromorphism, which is common in the Ivrea rocks along the Insubric Line, may be studied in detail in basic and ultrabasic rocks.

2. **Alluvial cone of the Riale Arsa east of Rumianca**
   Boulders of garnet and hornblende bearing orthopyroxene-clinopyroxene-labradorite or -bytownite rocks (pyriclasites) and stronalites from the mantle of the northern antiform.

3. **Alluvial cone of the Rio dell'Inferno**
   Ultrabasic rocks (principally olivine rocks, in rare cases retromorphic garnet-peridotites), garnetiferous orthopyroxene-clinopyroxene-hornblende-andesine/labradorite rocks (garnet-pyroxene-hornblende granofelses), pyriclastes and stronalited from the mantle of the northern antiform.

4. **Quarry of Anzola**
   Orthopyroxene-clinopyroxene-hornblende-andesine/labradorite/bytownite rock (pyroxene-hornblende granofels), containing pegmatitoides (clinopyroxene-orthopyroxene; andesine/labradorite/bytownite-clinopyroxene-orthopyroxene, +- hornblende, apatite, scapolite, sphene and quartz). Garnet clinopyroxene rocks in the contact zone between pyroxene-hornblende granofels, and orthopyroxene bearing stronalite at the eastern border of



ig. 2. Petrographical map of the lower part of the Valle d'Ossola, after SCHILLING (1957), ORIANI (1966) and SCHMID (1967), with observation points 1—10 of the excursion.

Figure 6.10: Geologic map and stops for Ivrea-Verbano Zone. From *Schmid* (1968).

the quarry. N-S striking mylonite. The labradorite and bytownite grains of the pyroxene-hornblende granofelses are unmixed into microscopic to submicroscopic lamellae.

5. **Quarry of Nibbio (behind the Chapel of Nibbio)**
   Amphibolite of Nibbio. The amphibolite is fine banded: the dark bands consist of green hornblende and plagioclase and minor amounts of clinopyroxene, the light bands of clinopyroxene, plagioclase and minor amounts of hornblende, scapolite, epidote and calcite. (Plagioclase: andesine, labradorite or bytownite). Accessories: ore, sphene and apatite. The amphibolite contains pegmatitoides consisting of microcline and/or calcite +- garnet, clinopyroxene, epidote, sphene, biotite, ilmenite, scapolite and quartz. In the outcropping amphibolite: vertically dipping layers of stronalite with modal ratios g$\sim$0. In the lower part of the outcrop: entrance to the tunnel of an abandoned mine (Ni-bearing pyrrhotite, chalcopyrite, and sphalerite).

6. **Alluvial cone northwest of Bettola**
   Boulders of kinzigite gneisses and amphibolites of the type in Nibbio. The biotite of the kinzigite gneisses gives a K-Ar age of 171 Ma.

7. **Between Bettola and Albo**
   Top part of a pyroxene-hornblende granofels fold. Isolated occurrence of this rock type among common amphibolites which may be seen 15 m above the fold.

8. **Church between Albo and Candoglia**
   Kinzigite gneiss with quartz-feldspar veins and lenses. Thin amphibolite band.

9. **Path from the Church “La Guardia” above Ornavasso to**

10. **Teglia**
    Kinzigite gneisses, patch amphibolite of Albo, other amphibolites, pegmatites. Marvellous view of the structures on the other side of the Valle d’Ossola.

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