by Alfonso Bosellini, Piero Gianolla, and Marco Stefani

Geology of the Dolomites

Dipartimento di Scienze della Terra, Corso Ercole I d'Este 32, 44100 Ferrara, Italy.

The Dolomites region is a spectacularly exposed portion of the Southern Alps, a northern Italian chain derived from the comparatively gentle deformation of the Tethyan passive continental margin of Adria. The region had an active Permo-Jurassic tectono-magmatic evolution, leading from Permian magmatism, through a Middle Triassic episode of fast subsidence and volcanism, to the Jurassic oceanic break-up. Although the sedimentary succession ranges in age from Middle Permian to Cretaceous, the geological landscape is largely dominated by the majestic Triassic carbonates, making the area a classical one for the early Mesozoic stratigraphy. Particularly noteworthy are the Anisian to Carnian carbonate platforms, recording an evolution from regional muddy banks to isolated high-relief buildups. The filling of the various basins and the development of a last generation of regional peritidal platform followed. The carbonate platforms of the Dolomites bear witness to a remarkable set of changes in the carbonate production and to significant palaeoclimatic fluctuations, from arid to moist conditions and vice versa; a great range of margin and slope depositional styles is therefore recorded. Alpine tectonic shortening strongly affected the area, with a first Eocene deformation, followed by later Neogene overthrusting and strike-slip movements.

Introduction

The purpose of this article is to introduce the reader to the general geology of the Dolomite Region. Discussion, however, will be focused on the majestic Triassic dolomite mountains, considered worldwide as typical examples of ancient carbonate platforms and buildups. Since the second half of the 19th century, the seminal studies by Richthofen (1860) and Mojsisovics (1879) recognized the reefal nature of the Dolomite Mountains, described and correctly interpreted the steep clinostratification pattern, identified several generations of platforms and provided a first biostratigraphic framework.

After dwindling research and reduced interest through the first half of the 20th century, great attention was again focused on the Triassic reefs and buildups, eventually leading to a modern synthesis of their depositional geometries and evolution (Bosellini, 1984). During the last twenty years, further substantial progress in the understanding of the geological evolution of the "reefs" has been achieved: the biostratigraphic and chronological framework was significantly improved (Brack and Rieber, 1993; Mietto and Manfrin, 1995), the main carbonate producing biota were recognized (Senobari-Daryan et al., 1993; Russo et al., 1998, 2000), and the origin of the platform-top sedimentary cyclicity has been the theme of a hot debate (Goldhammer et al., 1990; Brack et al., 1996; Egenhof et al., 1999; Preto et al., 2001), without, for the time being, reaching any firm conclusion. Finally, an improved knowledge of the basinal successions has made the integration with their platform counterparts possible, leading to a far better understanding of the sequence stratigraphic architecture (Gianolla et al., 1998a and references therein).

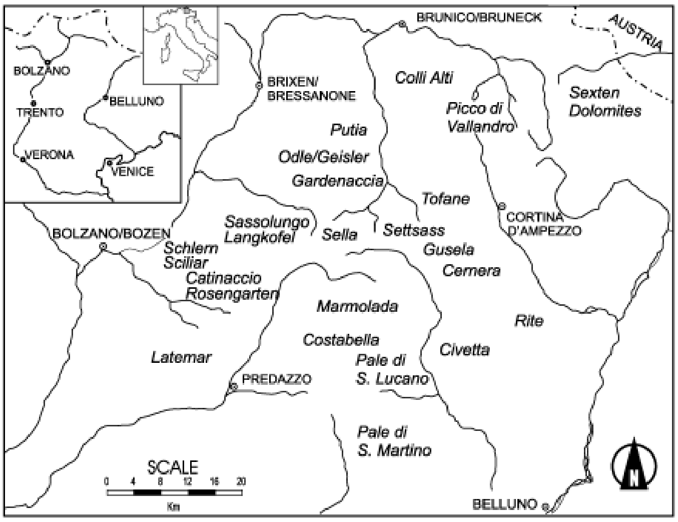

***Figure 1** Location map of the Dolomites (northern Italy), with indication of the most important platforms and buildups.*

Structural setting

The Dolomite Mountains are a group of carbonate edifices relatively well confined from the physiographic point of view (Figure 1). They are located in the eastern part of the so-called Southern Alps, a south-vergent fold-thrust belt (Doglioni, 1987; Castellarin, 1996), which constitutes a major structural unit of the Alpine Chain. The Dolomites themselves can be seen as a large pop-up related synclinorium of Neogene age (Doglioni, 1987), limited to the north by the dextral Insubric Lineament and to the south by the Neogen south-vergent Valsugana Overthrust (Figure 2). They constitute a relatively coherent slab of upper crust carried southward for at least 8–10 km. The sedimentary cover, preserved within this 60-km-wide synclinorium, is comparatively mildly deformed by tectonics; intense penetrative deformation as well as very large horizontal displacements do not occur. The region, however, records several magmatic and tectonic events including:

1. Volcanics and rifting of Permian and Early Triassic age, which produced N-S trending structural "highs" and "lows";
2. Late Ladinian magmatism and tectonics;
3. Rifting and continental margin evolution, associated with the opening of the western Tethys (Ligurian Ocean), which controlled differential thickness and facies during Late Triassic, Jurassic and Early Cretaceous times;
4. Paleogene N60ºE (Dinaric) compression producing a WSW-vergent thin-skinned thrust belt in the central-eastern Dolomites (Doglioni and Bosellini, 1987);
5. Finally, during the Neogene, the Dolomites became the innermost part of a south-vergent thrust belt (Figure 2); most of the present elevation has been generated during the last 10 million years.

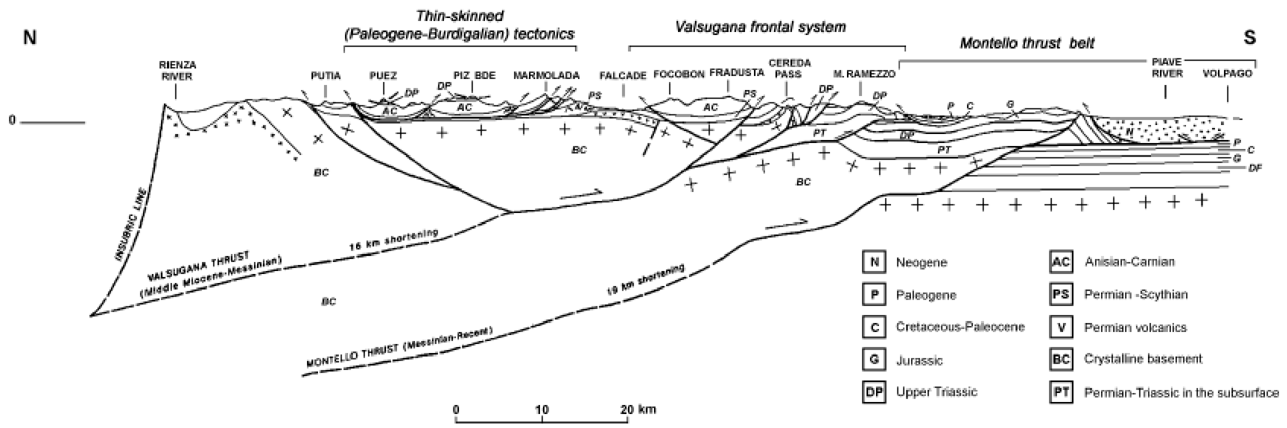

Figure 2 Geological profile across the western Dolomites (from Castellarin et al., 1998).

Regional stratigraphy

The stratigraphic framework of the Dolomite region includes Permian to Cretaceous terrains (Figure 3). Following the Carboniferous Variscan orogeny, deformed and metamorphosed Paleozoic rocks were uplifted and eroded, thus forming the regional basement.

The Early Permian rifting resulted in the accumulation of a thick volcanic package, the so-called Bozener Porphyry Plateau. This volcanic complex covers over 2000 sq. km, with thicknesses locally exceeding 2000 m. The sedimentary succession of the Dolomites unconformably overlies the Lower Permian volcanics or, where they are missing, rests directly on the crystalline basement. It begins with Upper Permian red beds (Gardena Sandstone) deposited in a semi-arid setting of alluvial fans, braided streams and meandering rivers (Massari and Neri, 1997). Following marine transgression from the Paleothethys to the east, transitional and shallow marine evaporites and carbonates (Bellerophon Formation) succeed upward in the Late Permian. Facies associations of the Bellerophon Formation suggest a wide spectrum of depositional environments, ranging from coastal sabkha to shallow shelf (Bosellini and Hardie, 1973; Massari and Neri, 1997).

The Lower Triassic Werfen Formation unconformably overlies the Permian sequence and consists of a complex succession of shallow-water carbonate and terrigenous deposits. The Werfen Formation is 300–400 m thick and is subdivided into several depositional sequences, recognizable over a wide portion of the Southern Alps.

During the early Middle Triassic, local uplifting, subaerial erosion and strong subsidence took place. Differential movements along fault blocks set the stage for localized carbonate production: the Middle Triassic carbonate platforms and buildups nucleated upon slightly elevated areas.

The Anisian platforms

A first widespread tidal flat unit (Lower Serla Dolomite), laterally grading into evaporitic environments, gave way to a complex framework of three partially superimposed carbonate platform systems: Monte Rite Formation, Upper Serla Dolomite and Contrìn Formation. Because of a general sea-level rise, the lower two platform systems drowned and long-lasting basinal environments, recorded by terrigenous-carbonate successions (Dont, Bivera and Ambata formations), succeeded in the eastern Dolomite. During the late Anisian, while subsidence was still active throughout the eastern Dolomites, the western area was significantly uplifted and subaerially eroded, locally exposing Permian sediments (Bosellini, 1968). Renewed transgression brought back marine environments to the western areas, where shallow-water carbonate platforms (Contrìn Formation) devel-

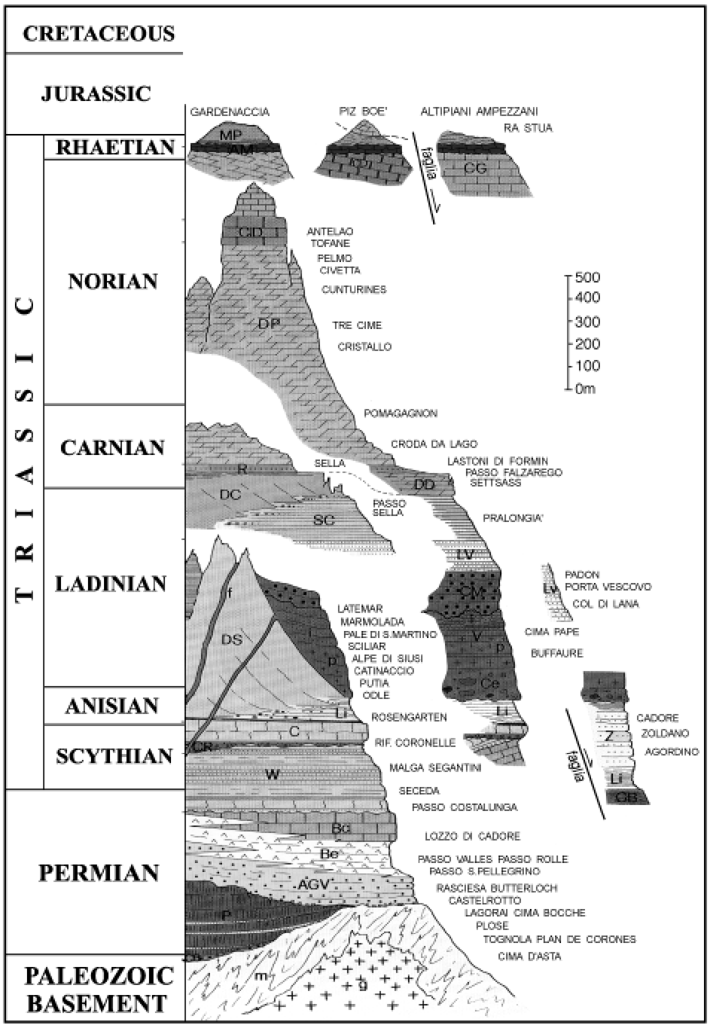

Figure 3 Composite stratigraphic succession of the central-western Dolomites. Granite (g); metamorphics (m); Basal Conglomerate (BC); Porphyry (P); Gardena Sandstone (GS); Bellerophon Fm: Black limestone (Bl), Evaporites (Be); Werfen Fm. (W); Braies Group (GS); Richthofen Conglomerate (CR); Contrin Fm. (C); Livinallongo Fm. (B); Zoppè Sandstone (Z); Sciliar Dolomite (SD); Volcanics (V): pillow lava (p), hyaloclastites (h), chaotic heterogeneous (Ch), dykes (d); La Valle Fm. (FM, LV), Marmolada Conglomerate (MC); San Cassiano Fm. (SC); Cassian Dolomite (CD); Dürrenstein Fm. (DD); Raibl Fm. (R); Dolomia Principale (DP); Dachstein Limestone (CD); Calcari Grigi (CG); Rosso Ammonitico (RA); Puez Marl (MP).

oped. These platforms, rich in dasycladacean algae, associated with encrusting and *problematica* organisms (*Tubiphytes*), widely prograded over lagoonal-basinal terrigenous-carbonate deposits (Morbiàc Formation).

The pre-volcanic carbonate buildups (late Anisian–late Ladinian)

A regional drowning terminated the previous Anisian platform and basin system, but shallow-water carbonate-producing environments "survived" at small isolated highs. Soon, however, these banks grew quickly upward by aggradation, forced by a phase of regional subsidence, which created a large accommodation space. These aggrading banks or buildups initially shared many facies similarities with the former and wider Contrìn platforms, being still rich in dasycladacean and *Tubiphytes* muddy sediments. The upward growth of some buildups was terminated by an early drowning, especially in the eastern, more subsiding portion of the region (Cernera, Casera Plotta, Tiarfin) and were covered by condensed ammonoid-bearing limestones (Gianolla et al., 1998a). The western buildups (referred to as Sciliar Dolomite or Marmolada Limestone, according to their composition), were on the contrary able to survive and catch up with the fast-growing relative sea level (e.g. Latemar, Catinaccio, Marmolada, Pale di San Martino). These platforms rapidly reached a thickness of 800–900 m, while just a few metres of cherty limestones were accumulating in the adjacent basins (lower portion of the Livinallongo Formation). In the eastern Dolomites, both the basinal and the platform successions are thicker then their western counterparts.

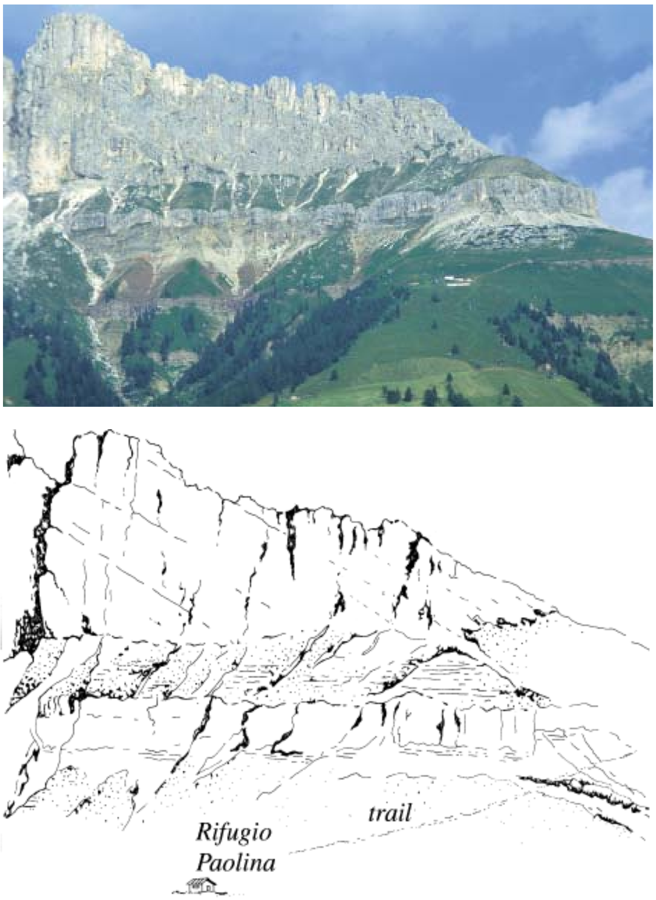

Figure 4 The southern end of the Catinaccio/Rosengarten platform, where the steep clinoforms show the horizontal progradation of the carbonate system.

The aggradation rate of these late Anisian-early Ladinian buildups was in the order of 200–400 m/Ma, but significant lateral variations did exist, being largely controlled by the regional differential subsidence. However, problems in the geochronometric evaluation of the different time intervals make the estimation of the aggradation and progradation rate somewhat uncertain. At the Fassian-Longobardian boundary, the subsidence slacked considerably and a massive progradation phase began, spanning over a comparatively short time interval of the late Ladinian. The progradational phase was characterized by pervasive phreatic marine cementation of the margin and upper slope sediments and by the development of very steep (40–45°), planar breccia slopes (Figure 4). Since the progradation rate largely exceeded the basinal accumulation rates, the surface of contact between the base of slope and the basinal unit can be sharp and sub-horizontal in geometry, simulating a pseudo-downlap relationship. Through this fast and remarkable progradation, the isolated buildups expanded considerably and became platforms with a width in the order of 5–10 km. In the western Dolomites, the average progradation rate of the base of slope was probably between 1400 and 2700 m/Ma. In the northeastern Dolomites, where subsidence was still quite active, the rate of the base-of-slope migration was considerably reduced.

During the same time, acidic volcanogenic layers (the so-called "pietra verde") were deposited in the entire Southern Alps, whereas the eastern Dolomites were the site of an important accumulation of turbiditic sands (Arenarie di Zoppè), deriving from the erosion of a Variscan metamorphic basement. The terrigenous and volcanic deposits document an active tectonic scenario that was soon to generate an important magmatic phase within the Dolomites themselves.

The volcanic event

The platforms were involved in the Ladinian tectono-magmatic event; they were cut by a great number of shoshonitic basaltic dykes and carved by large collapses, while huge heterogeneous megabreccia bodies (Caotico Eterogeneo Auct.) accumulated in the basins. The volcanic products (pillow lavas, hyaloclastites) partially infilled the basinal depressions, onlapping the platform slopes and "freezing" their original morphology (Figure 5). A few platforms of the western Dolomites (Agnello, Latemar, Viezzena, Marmolada) close to the volcanoes were even buried beneath the volcanic products. Some kind of carbonate production was nonetheless still active all the time, even close to the major magmatic centres (e.g. Sciliar). In areas far away from the volcanoes (eastern Dolomites) the carbonate sedimentation was not interrupted; here the lack of any true depositional break within the continuous platform-top successions makes the distinction between pre- and post-volcanic succession locally difficult.

The post-volcanic platforms (late Ladinian–early Carnian)

At the fading of the magmatic activity, an even healthier carbonate production developed, supporting the widespread progradation of several generations of carbonate platforms (Cassian Dolomite). The post-volcanic platforms record the progressive colonization of the margin environment by Techosmilia-like branching corals, which were however always subordinated to smaller sediment-producing organisms. Ooid grains reappeared during the earliest phases of the volcanic activity (Acquatona Formation), after being absent since the Early Triassic.

In the western Dolomites, the available accommodation space was not produced by subsidence but mainly inherited from the pre-volcanic "collapse" of the area. The platform, therefore, could only expand laterally, prograding over the adjacent deep-water basins. In the eastern Dolomites the subsidence was still ongoing and considerable. Clinostratifications are concave in shape and generally less

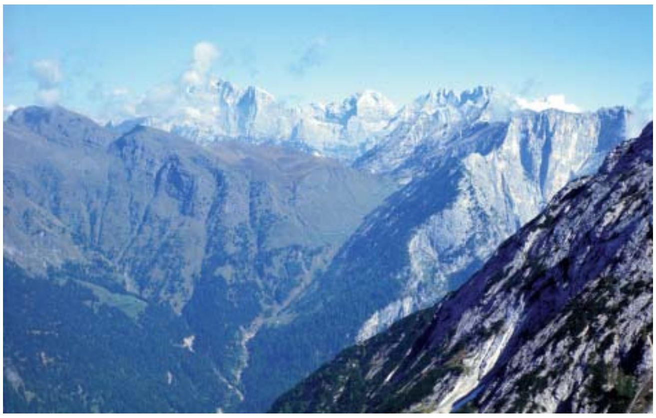

Figure 5 The western slope of the Pale di San Martino platform onlapped and "fossilized" by volcaniclastic products.

steep than the pre-volcanic ones (Figure 6). The high basinal sedimentation rates, owing to the large availability of volcaniclastic sediments, produced a shallowing evolution of the basinal areas. Moreover, the combined effect of the platform progradation and of the basinal aggradation resulted in climbing base-of-slope progradation, visible in areas facing major sediment sources (e.g. western Sella).

Early post-volcanic aggrading platform-top successions are relatively thick in the subsiding eastern Dolomites (e.g. Picco di Vallandro-Duerrenstein), whereas in the western Dolomites the same successions are very thin and associated with some terrigenous influx ("Schlern Plateau Beds"). In the central-eastern Dolomites, two platform generations (Cassian Dolomite I and II *Auct.*) are separated by a temporary interruption of the progradational evolution (Figure 7), matched with renewed transgression and with the onlap of the basinal beds onto the former carbonate slopes (e.g. Richthofen Riff and Settsass, etc.).

The Carnian crisis of the rimmed carbonate platforms

During the early Carnian (younger Julian), the amount of loose carbonate mud available in the prograding slopes increased, while the platform slope elevation was progressively reduced by the shallowing-up of the basin and by some terrigenous clay content; these factors combined together to progressively reduce the slope angles, as visible in the latest Cassian Platforms (e.g. Lastoi di Formìn and Picco di Vallandro/Dürrenstein). The very late evolution of these platforms was matched with the appearance of patch reefs, for the first time rich in "modern" colonial corals, while true buildup systems disappeared. This evolution corresponds to a worldwide crisis of the rimmed carbonate platforms.

The basin eventually shallowed up into the photic zone, probably also because of a relative sea-level drop, starting an *in situ* active carbonate production, even in the deeper depocentre areas. This evolution triggered the deposition of the low-gradient Dürrenstein Formation, which records a complex palaeoenvironmental evolution. In the western Dolomites, this Carnian interval is however poorly recorded, mainly because of the lack of available accommodation space. These complex depositional systems witness important climatic fluctuations, marked by the development of moist phases. This interval is also relevant for its bearing the oldest known Mesozoic amber (Gianolla et al., 1998b).

Figure 6 Oblique-tangential prograding pattern (Conturines Group-La Varella).

Figure 7 The "Richthofen Reef" (Piccolo Settsass). Thin-bedded shale and limestone of the San Cassiano Fm. onlap the slope of the buildup (Cassian Dolomite), which is wedging out towards the right with tongues of resedimented breccia and crinoidal grainstone.

The Upper Triassic carbonate platform: a regional peritidal succession

During the late Carnian (Tuvalian) the previous platform/basin systems were replaced by a variety of shallow-water environments (terrigenous, evaporite and carbonate sediments of the Raibl Formation). The preceding uneven morphology was levelled and a large carbonate platform was established over large portions of the Alpine region. In the central-western Dolomites, this carbonate system, the so-called Dolomia Principale, normally started with subtidal facies, grading upward into rapidly aggrading cyclic peritidal successions (Bosellini and Hardie, 1988). The eastern margin of this widespread peritidal platform lies in the Tarvisiano area, some 100 km at the east of the Dolomites. Here a well-preserved carbonate slope is documented by steep prograding clinostratifications, rich in serpulids, dasycladacean algae, microbial mats and pervasive phreatic cementation (De Zanche et al., 2000).

During the Norian Time, dis-anoxic intraplatform depressions, rich in carbonate mud and organic matter, developed in different areas of the vast Dolomia Principale platform, to the east (Friuli and Carnia), south (Bellunese) and west (Lombardia) of the Dolomites. In fact, differential subsidence, associated with widespread extensional processes, controlled the evolution of the Upper Triassic platforms, heralding the rifting stage of the Jurassic passive continental margin of Adria (African Promontory).

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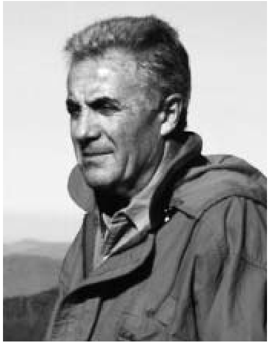
***Alfonso Bosellini** earned his degrees at the University of Padua. He held postdoctoral fellowships in the United States, at the Johns Hopkins University and Scripps Institution of Oceanography. His wide interests in structure, stratigraphy and carbonate sedimentology led him to study the Dolomites, Apulia, Somalia and Ethiopia. He is currently a professor of geology at the University of Ferrara, honorary fellow of the Geological Society of America and past president of the International Association of Sedimentologists.*



***Piero Gianolla** earned his PhD degree at the Padua University and currently holds a research position at the University of Ferrara. His main research fields consist in the sequence stratigraphy, paleoclimatological and sedimentological investigation of carbonate platforms and mixed basins. He is involved in a stratigraphic revision of the Triassic aimed at establishing a supra-regional sequence stratigraphic framework, through the correlation of sections from the Southern Alps, the Northern Calcareous Alps, the southern Appennines and Hungary.*

***Marco Stefani** received a PhD. degree in 1989, then worked in the Hydrocarbon Geology field and at the IFP, Rueil-Malmaison. He joined the Earth Sciences Department of the Ferrara University, Italy, in 1995, where he has been working ever since. His main research fields are the depositional dynamics of Triassic carbonate platform and basin systems and the Quaternary stratigraphy and G.I.S.-assisted geological mapping of the Po Delta Area.*