DOI:10.19276/plinius.2018.01008 PLINIUS n. 44, 2018

EMPLACEMENT OF THE MIDDLE TRIASSIC MONZONI INTRUSIVE COMPLEX (DOLOMITES, ITALY): INSIGHTS FROM ANALOGUE MODELS AND FIELD OBSERVATIONS

MARIA MICHAIL
Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Via Saragat 1, 44122, Ferrara

INTRODUCTION

The Dolomites are located in the central-eastern portion of the Southern Alps (Fig. 1), a South-verging fold-and-thrust belt that belongs to the much larger Alpine Orogeny (Carminati *et al*., 2010; Handy *et al*., 2010). The stratigraphic framework of the Dolomitic area includes mainly Permian to Cretaceous terrains and is largely dominated by the magnificent Triassic carbonate platforms and basinal systems. The Dolomites represent a worldwide reference area for the relationship between magmatism, sedimentation and tectonics (*e.g.*, Ogilvie Gordon, 1902; Vardabasso, 1930; Leonardi, 1967; Castellarin *et al*., 1982b; Visonà, 1997; Gianolla *et al*., 1998; Abbas *et al*., 2018).

During the Middle Triassic the Southwestern part of the Dolomites has witnessed a massive and short-lived Ladinian (Middle Triassic) tectono-magmatic event. Voluminous magmatic edifices developed together with the effusion of lavas (pillow lava and pillow breccias) and the deposition of volcaniclastics, coeval to the deformation of Permian to Middle Triassic sedimentary formations, with extensive vertical displacements (Viel, 1979a and b; Castellarin *et al*., 1982b; Bosellini *et al*., 1982; Doglioni, 1987; Abbas *et al*., 2018). The Monzoni Intrusive Complex together with those of Predazzo and Cima Pape, situated in the Southwestern part of the Dolomites, represent the main intrusive expressions of the Ladinian magmatism (Fig. 1).

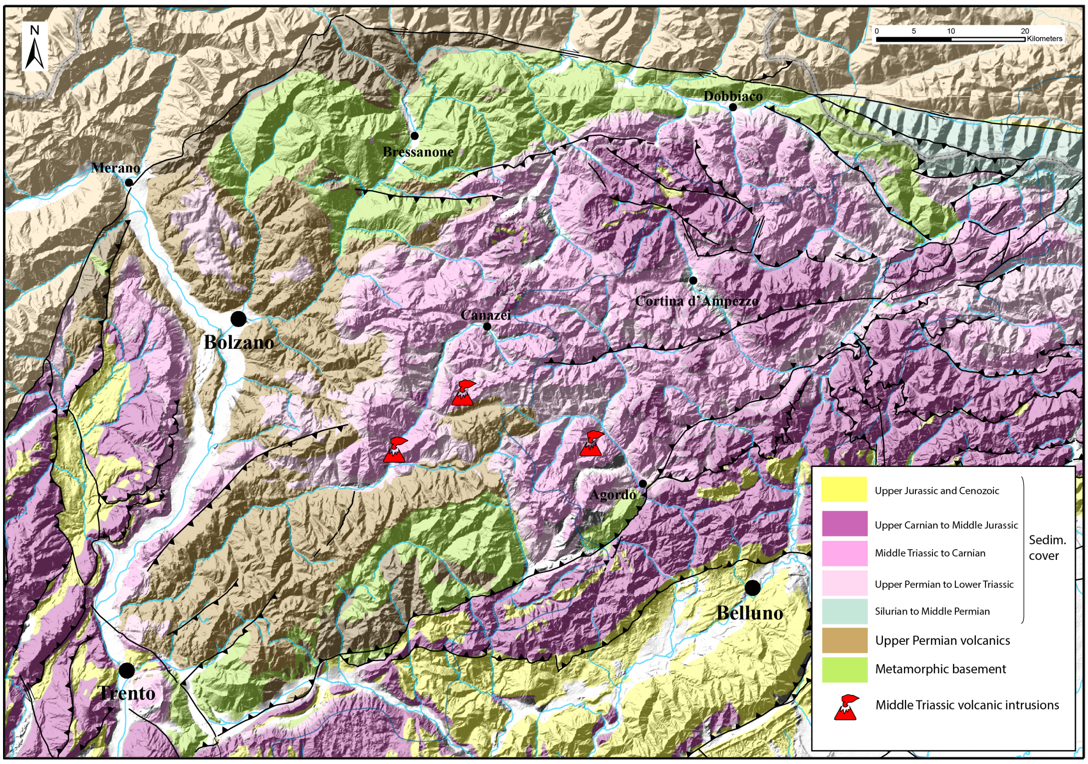

Fig. 1 - Simplified geological map of the Central-Western region of the Dolomites and the study area of the Monzoni Intrusive Complex (after Bosellini, 1996).

The magmatic intrusions together with an important number of quartz syenitic and shoshonitic dyke swarms intruded the Permo-Triassic sedimentary cover (Vardabasso, 1930; Castellarin *et al*., 1982a; Doglioni, 1983) whereas the volcanic products partially filled mostly the basinal depressions.

The Monzoni pluton, thanks to its excellent three-dimensional exposure, is particularly suited for the study of volcano-tectonic systems and the Middle Triassic magmatism.

Field campaign data, including sampling for measuring the anisotropy of magnetic susceptibility (AMS) of the pluton, in combination with analogue modelling observations on magmatic intrusions along shear zones (Román-Berdiel *et al*., 1997; Corti *et al*., 2005; Galland *et al*., 2015), bring new insights on the emplacement mechanisms of the Monzoni Intrusive Complex, the timing of emplacement and the interactions evolving between the pluton and the fault structures. In addition, the final 3D projection of the Monzoni defines the geometrical relations of the Intrusion Boundaries that control the pluton emplacement and deformational pattern of the host rocks, while the shape of the magmatic chamber is very well constrained.

GEOLOGICAL SETTING - THE LADINIAN MAGMATIC EVENT

The area of the Dolomites is part of the southern Alpine chain and forms a 60 km, South-verging thrust- and fold belt synclinorium, limited to the South by the Valsugana Overthrust, to the West by the Giudicarie fault system and to the North by the transpressive Periadriatic (Insubric) Lineament (Doglioni, 1987; Castellarin *et al*., 1998).

The stratigraphic framework of the Dolomitic region, in the Southern Alps, includes Permian to Cretaceous units that testify several tectonic and magmatic events recorded in the stratigraphic succession (Fig. 1), including the Permian extensional tectonics accompanied by massive acid magmatism (Visonà *et al*., 2007; Brandner *et al*., 2016), the Middle Triassic tectonics, associated with differential subsidence and uplift and diffuse magmatic events during the late Ladinian, Late Triassic and Jurassic rifting and several compressional Alpine deformation phases (Castellarin *et al*., 2006).

During Middle Triassic time, the Dolomites were affected by N 70°-90°E trending strike-slip faulting (along the Stava, Trodena and Cavalase Lines), locally associated with transtensional and transpressional tectonics.

Starting from the middle Anisian an important volcanic activity is documented in a large part of the western Tethys and in all the Southern Alps region as pyroclastic deposits and volcaniclastics (Viel, 1979a; Brack & Rieber, 1993). During the middle Ladinian a violent tectono-magmatic event, related with strong tectonic movements, affected the Dolomites (Borsi & Ferrara, 1967).

A massive intrusive and effusive magmatic activity developed (Viel, 1979a; Blendinger, 1985; Casetta *et al*., 2017; Abbas *et al*., 2018), deforming and intruding the pre-existing carbonate platforms. A large number of basaltic dykes appear to cut the formations, whereas huge heterogeneous megabreccia bodies (Caotico Eterogeneo) accumulated into the adjacent depressions.

Volcanic products basaltic (pillow lavas, hyaloclastites) partially filled the former basins, fossilizing the previous platform morphology by onlapping their slopes.

The Middle Triassic magmatism delineates a shoshonitic trend, both in the effusive and subvolcanic units, suggesting that the magma derived from a deep mantle source, modified by earlier subduction events with a clear amount of crustal contamination (Rossi *et al*., 1976; Castellarin, 1983; 1998; Bonadiman *et al*., 1994; Abbas *et al*., 2018). The Monzoni Complex, together with Predazzo and Cima Pape, formed during this event and represent the most important co-magmatic complexes of the Dolomitic area (Fig. 1).

The age and duration of the short-lived Upper Ladinian magmatic event in the Dolomites is well constrained and defined by biostratigraphy and geochronology, revealing a time interval of < 0.7 Myr. Zircon dating from the granitic phase of the Predazzo intrusion, that is located 8 km to the SW of the Monzoni body, has shown an absolute age of 237.3 ± 1.0 Ma (Mundil, 1996; Brack et al., 1997).

The Monzoni Intrusive Complex

The Monzoni pluton (Fig. 1 and 2) is located parallel to San Pellegrino Valley and appears elongated (~ 4 km), with an NE-SW orientation, covering an area of approximately 8 km2. The intrusion consists of a series of basic to intermediate plutonic units, involving the gabbroic rocks (gabbro, olivine gabbro, monzogabbro), cropping out in the north-eastern part of the complex together with clinopyroxenite, whereas monzonites and monzodiorites dominate the western part of the pluton (Del Monte et al., 1967; Bonadiman et al., 1994; Gallien et al., 2007; Abbas et al., 2018; Fig. 2). The host-rock formations of the Monzoni Complex (Fig. 2) comprise the lower Permian acidic volcanic rocks of the Athesian Volcanic Group (Marocchi et al., 2008), the Upper Permian fluvial red beds of Val Gardena Sandstones (~100 m thick), the Upper Permian marls and evaporites of the Bellerophon Fm. (~300 m), the Lower Triassic carbonate Werfen Fm. (~280-500 m), the middle Anisian carbonate-siliciclastics units from Richthofen to Contrin Fm. (~150-200 m), the Sciliar carbonate platform (~800 m) and the limestones of Buchenstein Fm (< 80 m).

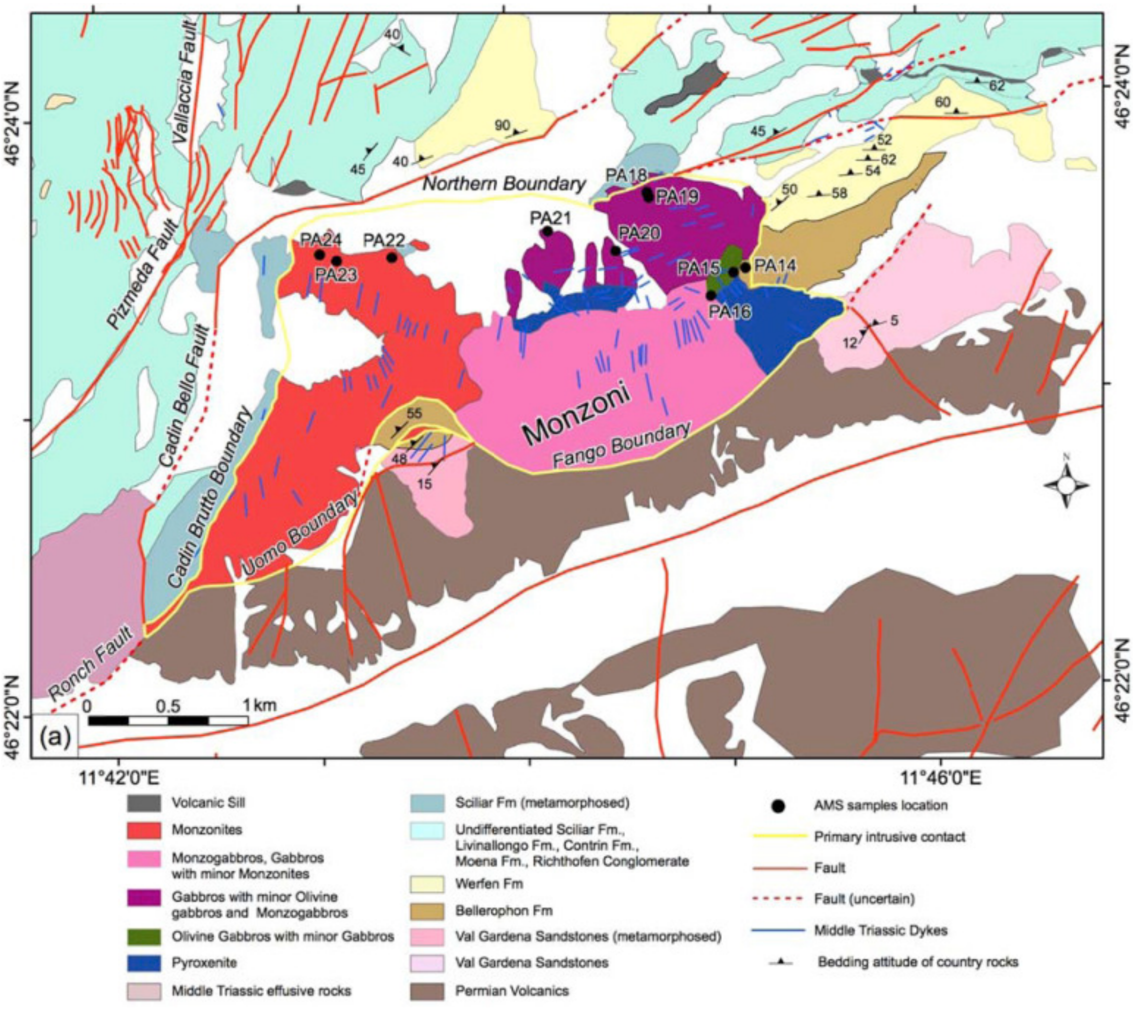

Fig. 2 - Simplified geological map of the Monzoni Intrusive Complex and its host-rock formations. On the map the Boundaries and Fault surfaces are projected. Black dots indicate the location of the sampling sites for AMS analysis (from Abbas *et al*., 2018).

The pluton together with the volcanic and effusive units (pillow breccias, hyaloclastites and volcanoclastic sandstones) delineates a calc-alkaline to shoshonitic trend (Sloman, 1989; Bonadiman et al., 1994; Marrocchino et al., 2002). The "orogenic" character of the Monzoni intrusive complex, in combination with the intrusion's NE-SW and its zonal arrangement, suggested a strong relation between its emplacement mechanism and strike-slip faulting, active during the Middle Triassic (Sloman, 1989; Doglioni, 1987; Bonadiman et al., 1994; Abbas et al., 2018). However, the main geometrical characteristics of the Monzoni suggest a potential correlation and emplacement control by the Triassic developing and/or reactivated inherited strike-slip structure.

METHODOLOGY

Tectonic control on the ascent and emplacement mechanisms of magma, and the interactions evolving between the pluton, the brittle upper crustal layers and the fault structures, have been a matter of long debate. To better understand the specific natural prototype and investigate the space and time relationship between the Ladinian Monzoni plutons and Middle Triassic strike-slip faulting, analogue model experiments on magmatic intrusions along shear zones defined by, but not limited to, first order field observations, were performed.

Fieldwork and sampling

Mapping and sampling for petrographic and AMS analyses were carried out in Monzoni intrusive body, in collaboration with *Università di Roma La Sapienza* and *Università degli Studi Roma Tre*. The AMS technique provides a quick and accurate indication of igneous rock magnetic fabric (lineation and foliation) thus, can specify the primary magma flow in magmatic sheet intrusions (Andersson *et al*., 2016). The samples were collected from 10 sites for a total of 84 cylindrical cores, drilled by using an ASC 280E petrol-powered portable drill and oriented *in situ* by a magnetic compass (Fig. 2 and 3).

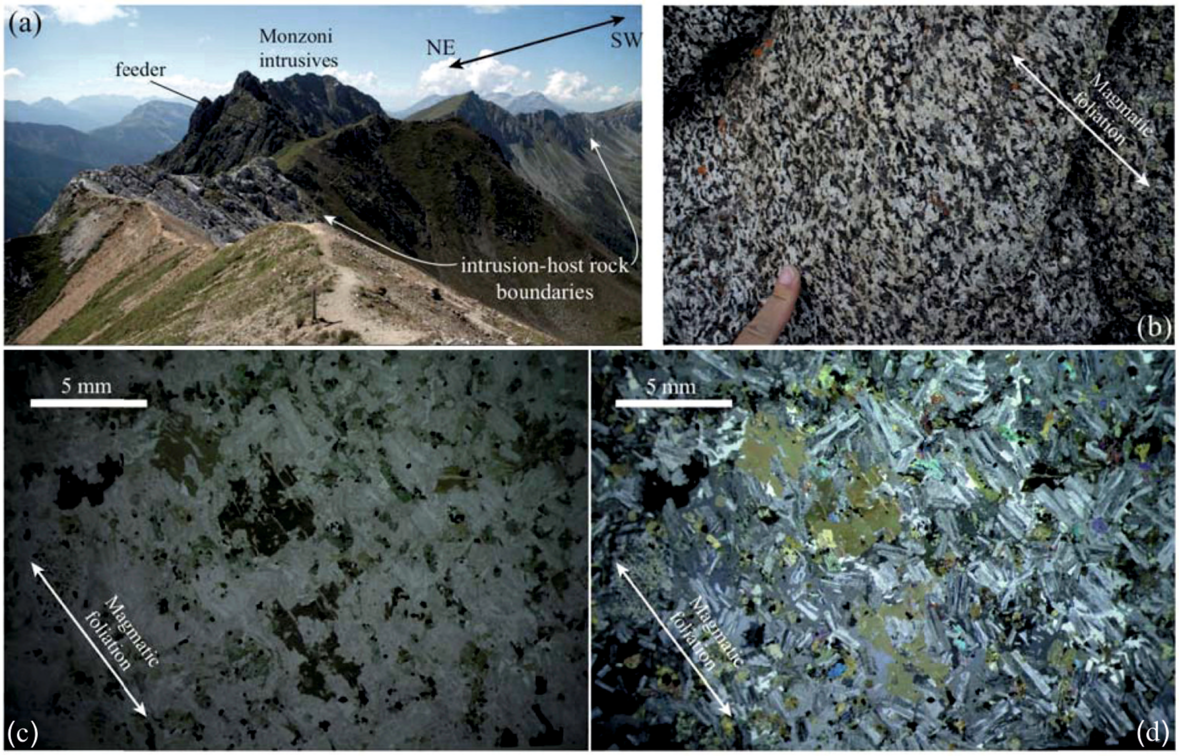

Fig. 3 - a) Monte Monzoni crest, showing the contacts between intrusive and *host rocks*. The location of the feeder area is also shown; b) Monzogabbro from the Monzoni body showing a well-defined magmatic foliation; c, d) Monzonite showing preferred orientation of plagioclase and biotite crystals (sample PA22a, same location of sample 22), plane-polarized and cross-polarized light respectively (from Abbas *et al*., 2018).

Analogue modelling

To better understand the general mechanisms of magmatic intrusions in tectonically active areas, a systematic series of analogue experiments, simulating magma emplacement along shear zones, was performed at the *HelTec - Helmholtz Laboratory for Tectonic Modelling - GFZ* in Potsdam (Germany) and at *University of Olso* (Norway). The ratio of viscous to brittle stresses between magma and country rock was varied, by injecting Newtonian fluids of high and low viscosity into granular analogue materials of varying cohesion. Digital image correlation allowed a quasi-continuous quantitative monitoring of the topographic evolution and surface deformation at high spatio-temporal resolution that lead to the reconstruction of the 3D incremental and cumulative surface deformation pattern (*i.e.*, velocity fields, strain fields and topography). Finally, high-resolution digital elevation models of the surface and intrusion were produced and classified (Fig. 4c).

CONCLUSIONS

The application of multiply research techniques lead to the deeper understanding of the long-lasting issue of magmatism and tectonic interactions and to constraining the emplacement mechanisms of the Monzoni Intrusive Complex. The detailed mapping and petrographic analysis (Fig. 3c and d) of the pluton, coupled with the investigations on anisotropy of magnetic susceptibility (AMS) on Monzoni pluton, revealed zonation within the pluton (Fig. 2) and indicated the presence of the magmatic feeder at the NE edge of the body (Abbas *et al.*, 2018; Fig. 3a and 4d). In addition, the ENE-WSW elongated shape of the Monzoni intrusion (Fig. 2 and 4a) seems to have been controlled by the occurrence of strike-slip fault system (Fig. 4b) associated with Ladinian-tectonics. However, the absence of deformation at the field- and micro-scale is consistent with a post Ladinian-tectonics timing of emplacement.

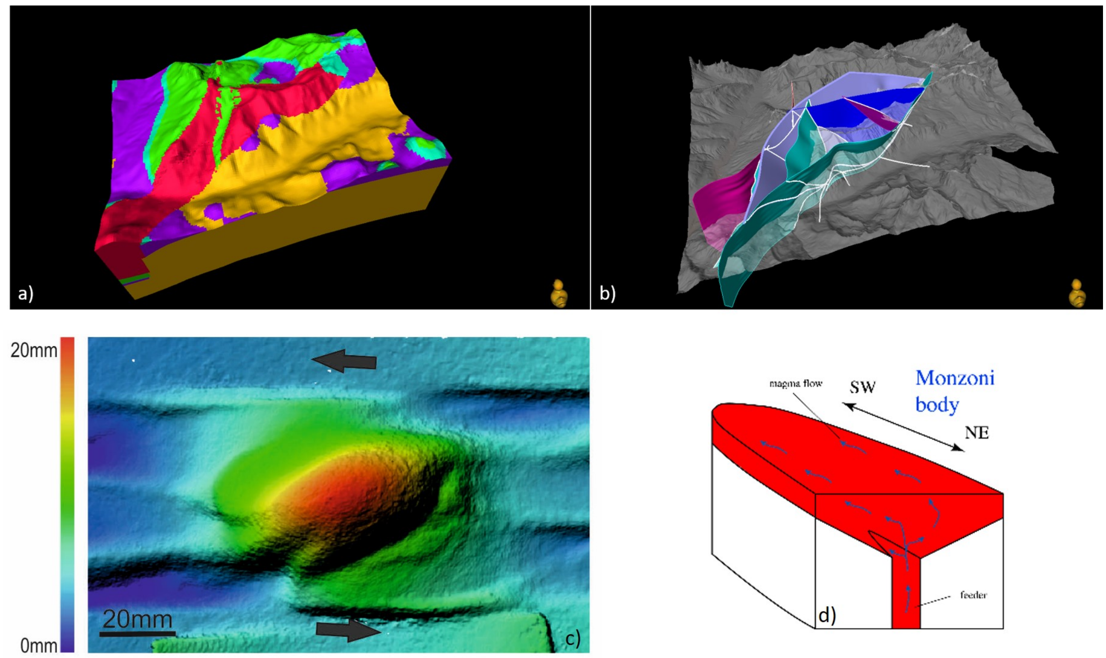

Fig. 4 - a) 3D grid of the Monzoni plutona and the host rock formations, indicating the deformational pattern along the fault structures [Stratigraphic layers: (orange) Top of Permian Volcanics, (purple) Top of Werfen Formation, (blue) Top Contrin/Moena Formations, (green) Top Sciliar Formation, (red) intrusion-volcanics]; b) 3D projection of the modelled Monzoni fault system; c) Digital elevation model of the final model pluton emplaced in strike-slip tectonic regime (GFZ-Potsdam); d) Sketch of the proposed emplacement mode for the Monzoni body (from Abbas *et al.*, 2018).

The experimental results*,* showed that there is a strong interaction between tectonic structures, evolving or inherited, and magmatism (Fig. 4c) and that the geometrical characteristics of the model plutons represent a good indicator for the classification of intrusions, defining the timing and tectonic setting of emplacement. Finally, the 3D modelling of the Monzoni Intrusive Complex, projecting all geological data, constrains the pluton's volume to 4.35 km^3 and offers a simplified projection of the pluton/host-rock system (Fig. 4a and b).

REFERENCES

Abbas, H., Michail, M., Cifelli, F., Mattei, M., Gianolla, P., Lustrino, M., Carminati, E. (2018): Emplacement modes of the Ladinian plutonic rocks of the Dolomites: Insights from anisotropy of magnetic susceptibility. *J. Struct. Geol*. **113**, 42-61.

Andersson, M., Almqvist, B.S.G., Burchardt, S., Troll, V.R., Malehmir, A., Snowball, I., Kübler, L. (2016): Magma transport in sheet intrusions of the Alnö carbonatite complex, central Sweden. *Sci. Rep. UK*, **6**, 1-13.

Blendinger, W. (1985): Middle Triassic strike-slip tectonics and igneous activity of the Dolomites (Southern Alps). *Tectonophysics*, **113**, 105-121.

Bonadiman, C., Coltorti, M., Siena, F. (1994): Petrogenesis and T-fO2 estimates of Mt. Monzoni complex (Central Dolomites, Southern Alps): a Triassic shoshonitic intrusion in a transcurent geodynamic setting. *Eur. J. Mineral.*, **6**, 943-966.

Borsi, S. & Ferrara, G. (1967): Determinazione dell'età delle rocce intrusive di Predazzo con i metodi del Rb/Sr e K/Ar. *Miner. Petrogr. Acta*, **13**, 45-66.

Bosellini, A. (1996): Storia Geologica delle Dolomiti. Athesia, Bolzano. 182 p.

Bosellini, A., Castellarin, A., Doglioni, C., Guy, F., Lucchini, F., Perri, M.C., Rossi, P.M., Simboli, G., Sommavilla, E. (1982): Magmatismo e tettonica nel Trias delle Dolomiti. *In*: "Guida Alla Geologia Del Sudalpino Centro-Orientale", Castellarin & Vai, eds. Guide Regionali Società Geologica Italiana, 189-210.

Brack, P. & Rieber, H. (1993). Towards a better definition of the Anisian/Ladinian boundary: new biostratigraphic data and correlations of boundary sections from the Southern Alps. *Eclogae Geol. Helv*., **86**, 415-527.

Brack, P., Mundil, R., Oberli, F., Meier, M., Rieber, H. (1997): Biostratigraphic and radiometric age data question the Milankovitch characteristics of the Latemar cycle (Southern Alps, Italy): Comment and Reply. *Geology*, **25**, 471-472.

Brandner, R., Gruber, A., Morelli, C., Mair, V. (2016): Field trip 1. Pulses of neotethysrifting in the permomesozoic of the Dolomites. *Geo. Alp.* **13**, 7-70.

Carminati, E., Lustrino, M., Cuffaro, M., Doglioni, C. (2010): Tectonics, magmatism and geodynamics of Italy: what we know and what we imagine. *J. Virtual Explor*., **36**, doi:10.3809/jvirtex.2010.00226.

Casetta, F., Coltorti, M., Marrocchino, E. (2017): Petrological evolution of the Middle Triassic Predazzo Intrusive Complex, Italian Alps. *Int. Geol. Rev*. **60 (8)**, 1-21.

Castellarin, A., Lucchini, F., Rossi, P.L., Sartori, R., Simboli, G., Sommavilla, E. (1982a): Note geologiche sulle intrusioni di Predazzo e dei Monzoni. *In*: "Guida Alla Geologia Del Sudalpino Centro-Orientale", Castellarin & Vai, eds. Guide Regionali Società Geologica Italiana, 211-220.

Castellarin, A., Guy, F., Selli, L. (1982b): Geologia dei dintorni del Passo di S. Nicolò e della Valle di Contrin (Dolomiti). *In*: "Guida alla Geologia del Sudalpino Centro-Orientale", Castellarin & Vai, eds. Guide Regionali Società Geologica Italiana, 231-242.

Castellarin, A. (1983): Alpi e Alpi Meridionali. Magmatismo e tettonica triassica. *Mem. Soc. Geol. Ital*., **24**, 5-7.

Castellarin, A., Selli, L., Picotti, V., Cantelli, L. (1998): La tettonica delle Dolomiti nel quadro delle Alpi Meridionali orientali. *Mem. Soc. Geol. It*., **53**, 133-143.

Castellarin, A., Nicolich, R., Fantoni, R., Cantelli, L., Sella, M., Selli, L. (2006): Structure of the lithosphere beneath the Eastern Alps (southern sector of the TRANSALP transect). *Tectonophysics*, **414**, 259-282.

Corti, G., Moratti, G., Sani, F. (2005): Relations between surface faulting and granite intrusions in analogue models of strike-slip deformation. *J. Struct. Geol*., **27**, 1547-1562.

Del Monte, M., Paganelli, L., Simboli, G. (1967): The Monzoni intrusive rocks. A modal and chemical study. *Mineral. Petrogr. Acta*., **13**, 75-118.

Doglioni, C. (1983): Duomo Medio-Triassico nelle Dolomiti. *Rend. Soc. Geol. It*., **6**, 13-16.

Doglioni, C. (1987): Tectonics of the Dolomites (southern Alps, northern Italy). *J. Struct. Geol.*, **9**, 181-193.

Galland, O., Holohan, E., Van Wyk De Vries, B., Burchardt, S. (2015). Laboratory Modelling of Volcano Plumbing Systems: A Review. *In*: "Physical Geology of Shallow Magmatic Systems", C. Breitkreuz & S. Rocchi, eds. Advances in Volcanology (An Official Book Series of the International Association of Volcanology and Chemistry of the Earth's Interior), Springer, 1-68.

Gallien, F., Abart, R., Wyhlidal, S. (2007): Contact metamorphism and selective metasomatism of the layered Bellerophon Formation in the eastern Monzoni contact aureole, northern Italy. *Miner. Petrol.,* **91 (1-2)**, 25-53.

Gianolla, P., De Zanche, V., Mietto, P. (1998): Triassic sequence stratigraphy in the Southern Alps (Northern Italy): definition of sequences and basin evolution. *In*: "Mesozoic and Cenozoic Sequence Stratigraphy of European Basins", P.-C. de Graciansky, J. Hardenbol, T. Jacquin, P.R. Vail, eds. EPM Special Publication No. **60**, 719-747.

Handy, M.R., Schmid, S.M., Bousquet, R., Kissling, E., Bernoulli, D. (2010): Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps. *Earth Sci. Rev.*, **102 (3-4)**, 121-158.

Leonardi, P. (1967): Le Dolomiti. Geologia dei monti tra Isarco e Piave. Consiglio Nazionale delle Ricerche. Roma, 1019 p.

Marocchi, M., Morelli, C., Mair, V., Klötzli, U., Bargossi, G.M. (2008): Evolution of Large Silicic Magma Systems: New U-Pb Zircon Data on the NW Permian Athesian Volcanic Group (Southern Alps, Italy). *J. Geol*., **116**, 480-498.

Marrocchino, E., Coltorti, M., Visonà, D., Thirwall, M.F. (2002): Petrology of Predazzo magmatic complex (Trento, Italy). Abstract. *Geochim. Cosmochim. Ac.*, **66**, A486-A486.

Mundil, R. (1996): High Resolution U-Pb Dating of Middle Triassic Volcaniclastics: Verification of Tuning Parameters for Carbonate Sedimentation and Time-scale Calibration. Ph.D. dissert. Zurich, Swiss Federal Institute of Technology, No. 11767.

Ogilvie Gordon, M.M. (1902): Monzoni and upper Fassa. *Geol. Mag*., **9**, 309.

Román-Berdiel, T., Gapais, D., Brun, J.P. (1997): Granite intrusion along strike-slip zones in experiment and nature. *Am. J. Sci.*, **297**, 651-678.

Rossi, P.L., Viel, G., Simboli, G. (1976): Significato paleogeografico e magmatico-tettonico della serie vulcanoclastica ladinica superiore nell'area del monte Civetta. *Boll. Soc. Geol. Ital*., **95**, 433-458.

Sloman, L. (1989): Triassic shoshonites from the Dolomites, northern Italy: alkaline arc rocks in a strike-slip setting. *J. Geophys. Res*., **94**, 4655-4666.

Vardabasso, S. (1930): Carta geologica del territorio eruttivo di Predazzo e Monzoni: ufficio Idrografico del Magistrato alle Acque di Venezia. Scale 1:25000 2 sheet.

Viel, G. (1979a): Litostratigrafia ladinica: una revisione. Ricostruzione paleogeografica e paleostrutturale dell'area Dolomitica-Cadorina (Alpi Meridionali). 1a Parte. *Riv. Ital. Paleontol. Stratigr.*, **85 (1),** 85-125.

Viel, G. (1979b): Litostratigrafia ladinica: una revisione. Ricostruzione paleogeografica e paleostrutturale dell'area Dolomitica-Cadorina (Alpi Meridionali). 2a Parte. *Riv. Ital. Paleontol. Stratigr.*, **85 (2)**, 297-352.

Visonà, D. (1997): The Predazzo multipulse intrusive body (Western Dolomites, Italy). Field and mineralogical studies. *Mem. Sci. Geol.*, **49**, 117-125.

Visonà, D., Fioretti, A.M., Poli, M.E., Zanferrari, A., Fanning, M. (2007): U-Pb SHRIMP zircon dating of andesite from the Dolomite area (NE Italy): geochronological evidence for the early onset of Permian Volcanism in the eastern part of the southern *Alps. Swiss J. Geosci*., **100**, 313-324.