Deep-Water Volcaniclastic Fans: What Can We Learn from the Past?*

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Abstract

Volcanism is a surface process widely diffuse in space and time on the Earth, whose episodically, short-lived activation deeply impacts both proximal and distal environments. Despite of the increasing knowledge on its capability to produce, transport, and deposit detritus, volcanism is often not considered as an Earth surface process that might have shaped the sedimentary basins in the past, overall when volcanic edifices in source-to-sink systems are not preserved.

We present a resume of the state of art of the investigations that we are carrying out on the foreland and foredeep basins developed during the Oligocene times at the boundary between the European and the Adriatic plates. In these basins, wide turbidite fans have been fed by huge volumes of primary and secondary dispersal discharged by volcanic centers located from the SE France to the embryo of the Alpine Belt. Such fans, now structured in the Helvetic Nappes of the Western Alps (Taveyanne Sandstones) and the Sub-Liguri Nappes of the Northern Apennines (Val d'Aveto Formation), preserve peculiar features that have been investigated in terms of geometries, sedimentary structures, petrography, mineralogy, and chemistry, through the combination of different techniques (field clast counts, image analyses, sandstone petrography, XRD, SEM-EDS). The result is a multidisciplinary sketch of the capability of volcanism to strongly influence the sedimentation of distal (tens to hundreds of kilometers), deep-water basins independently from the tectono-climatic boundary conditions that either favor or not the production, transport, and deposition of detritus. As a consequence, this sketch highlights the role of volcanism in shaping sedimentary basins, as well as its importance as a "complete sedimentary factory", able to instantaneously deliver large amounts of sediments far away from the main source. This study also underlines the importance of the combination of the sedimentological and the volcanological approach to the identification of primary and secondary volcanic deposits, as their different physical, chemical, and mineralogical properties control primary and diagenetic features that largely influence fabric type textures and consequent rock petrophysical properties. All these findings must be considered the key break-through for a comprehensive evaluation of volcaniclastic reservoir properties.

Introduction

The study of the influence of volcanism on the deep-water sedimentary systems is one of the most intellectually stimulating frontiers in sedimentology and petroleum geology. The main challenge on the study of volcaniclastic sequences concerns the identification of the influence that volcanic events had on the source-to-sink. During a volcanic event, in fact, huge volumes of volcanic particles are produced and instantaneously transferred across the environment for tens to thousands of kilometers, being either directly discharged into basins or temporary dispersed in transfer zones (Smith, 1991; Manville et al., 2009). The capability of volcanoes to induce the accumulation of thick sequences despite the tectono-climatic conditions in the surrounding environments is regularly either underestimated or not considered in sedimentary models (e.g., Catuneanu et al., 2011), and a systematic characterization of volcanic/volcaniclastic deposits is still missing. This is particularly evident in approaching ancient volcaniclastic sequences of turbidite fans that lack a clear stratigraphic correlation with volcanic source areas (Di Capua and Groppelli, 2014).

In petroleum geoscience, volcaniclastic turbidite fans have been recognized as potential hydrocarbons reservoirs, but the presence of high portions of mechanically and mineralogically unstable components makes their primary and secondary features difficult to understand for reservoir quality predictions (Seeman and Scherer, 1984). Thus, an accurate definition of the volcano-sedimentary features in deep-water environments could represent a break-through for the prediction and evaluation of reservoir quality in volcaniclastics.

Through the development of a multidisciplinary standardized workflow, based on the recognition of the main sedimentological, petrographic and petrophysical features, integrated with a combination of high-resolution techniques approach (SEM-EDS and XRD), this study carries out an innovative on volcaniclastic deposits in deep-sea water systems, and their correlation with their generating events and post-depositional history. The Northern Apennines foredeep basin (Northern Apennines - Italy) and the Northern Alpine foreland basin (Western Alps - France and Switzerland) have been the object of this study. For the first time, a classification of the deep-water deposits has been proposed and three main categories have been recognized. These include: 1) non-, 2) syn-, and 3) post-volcanic deposits. In non-volcanic deposits, volcanic detritus may be present as particles eroded from ancient volcanic sequences, so volcanism had no influence on sedimentation. In syn-volcanic deposits, volcanic detritus is directly provided during or soon after a volcanic event. In post-volcanic deposits, volcanic detritus is supplied by the resedimentation of dispersed, unconsolidated volcanic detritus, so the progressive lithification of onland volcaniclastic deposits tends to proportionally decrease the amounts of volcanic particles in the deposits. For their peculiar features, the presented work mainly focuses on a detailed description of syn-volcanic deposits.

Syn-Volcanic Deposits as Potential Reservoir Rocks

Syn-volcanic deposits are primary and secondary dispersals settled during or soon after a main eruption event. Particles generally move and settle under extreme physical conditions (e.g., hot temperatures, high pressures). This implies strong lateral and vertical variations of the nature of their deposits. In addition, their interaction with the surrounding environmental conditions strongly affects their physical properties. A further distinction between syn-eruptive and post-eruptive deposits can be made on the base of the influence of volcanism on sedimentation.

Syn-Eruptive, Syn-Volcanic Deposits

Syn-eruptive deposits are all the deposits directly settled during eruptive episodes by pyroclastic density currents (PDCs). They are of great importance for petroleum systems, as they are featured by great thicknesses, strong lateral variations, and primary and secondary porosity controlled by the generating volcanic process, the conditions of the depositional environment (e.g., presence of water, presence of paleosurfaces), and their post-depositional history. PDCs, in fact, are hot flows that mix with cold water entering a subaqueous basin. The physical behavior of such flows determines their modification and eventually disaggregation during their underwater motion before settling.

If PDCs are disaggregated, the resulted deposits consist of a thick, well sorted basal deposit, enriched in angular volcanic particles, and a thinner mud cap of a mixed volcanic/non-volcanic composition. This body anatomy is common both in modern and ancient settings (e.g., Taveyanne Sandstones – Di Capua and Groppelli, 2016a). Even though such types of deposits are alike to the sandy debris flow deposits of Shanmugam (2002), petrographic analyses reveal that glass can develop in the intergranular spaces, decreasing the primary porosity and permeability. Secondary porosity and permeability is the result of glass devitrification and dissolution.

If PDCs are not disaggregated, the resulted deposits show primary volcanic textures (e.g., porphyric), hydrothermal modifications, with the growth of secondary mineralogical phases (e.g., pyrite), and secondary fractures generated by the fluidization of underlying sediments. Such fractures are the most prominent porosity features (Di Capua et al., 2016). In addition, glassy-welded eutaxitic texture might also develop in-between close accidental clasts, as the result of increasing internal pressures and shear along their boundaries (Di Capua and Groppelli, 2016b).

Post-Eruptive, Syn-Volcanic Deposits

Post-eruptive, syn-volcanic deposits derive from the rapid resedimentation of unwelded volcanic deposits soon after volcanic events. They are settled by flash flood events, such as lahars, whose motion is controlled by the kinetic interaction of particles. At the microscale, they are characterized by volcanic particles that plastically embed accidental detritus to form a pseudomatrix (sensum Dickinson, 1970). Thus, porosity and pore interconnection are generally low, but might increase thanks to the devitrification of glass particles and dissolution of minerals.

Conclusion

The presented work and classification show the importance of a multidisciplinary and multiscale approach in the identification of the temporal relationship between volcanism and sedimentation, considered the main factor controlling the physical, minero-chemical, diagenetic, and petrophysical properties of volcaniclastic sequences. This innovative approach provides a comprehensive evaluation of the reservoir properties of volcaniclastic sequences.

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AAPG GTW "Influence of Volcanism and Associated Magmatic Processes on Petroleum Systems"
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Volcaniclastics as potential hydrocarbon reservoirs

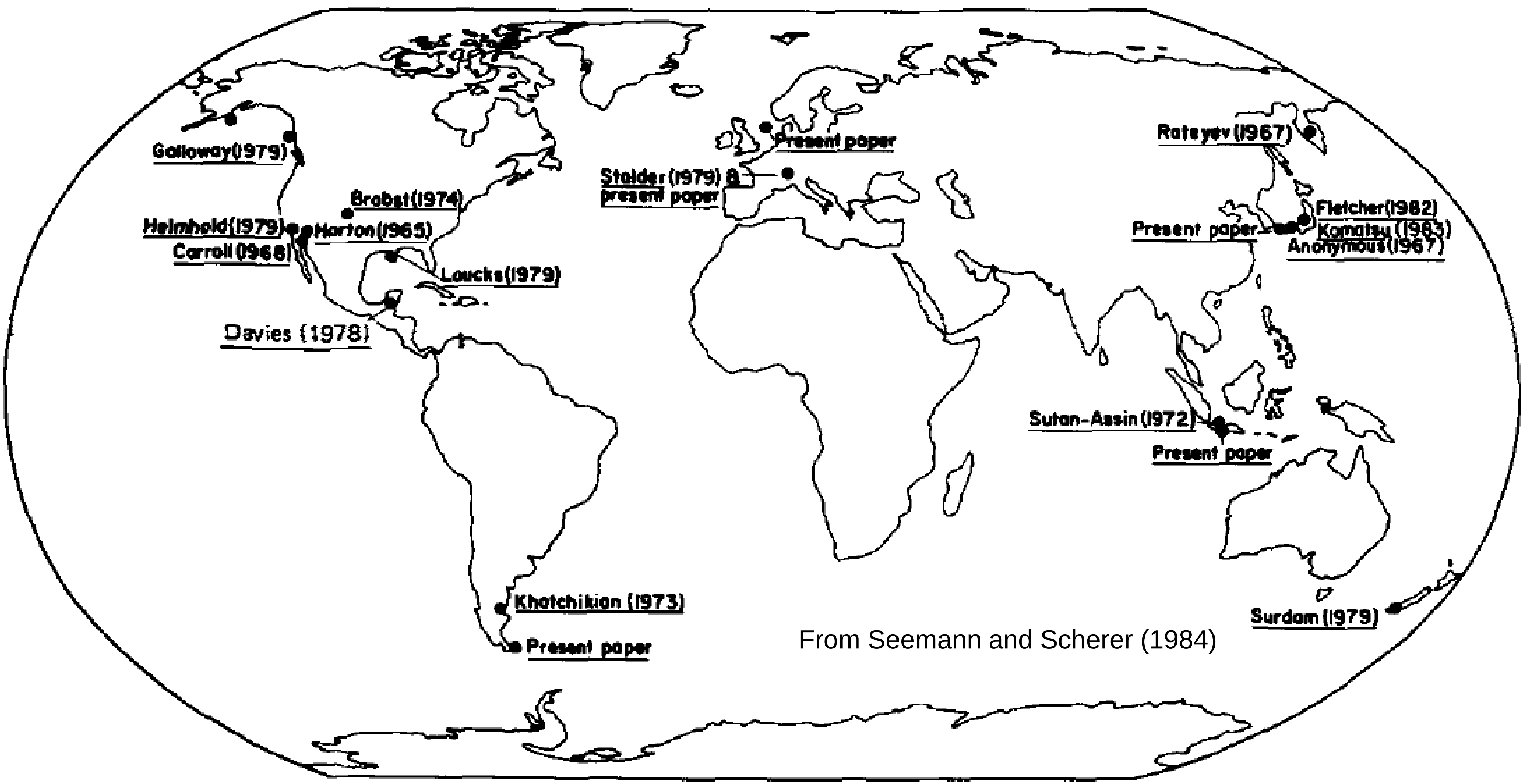
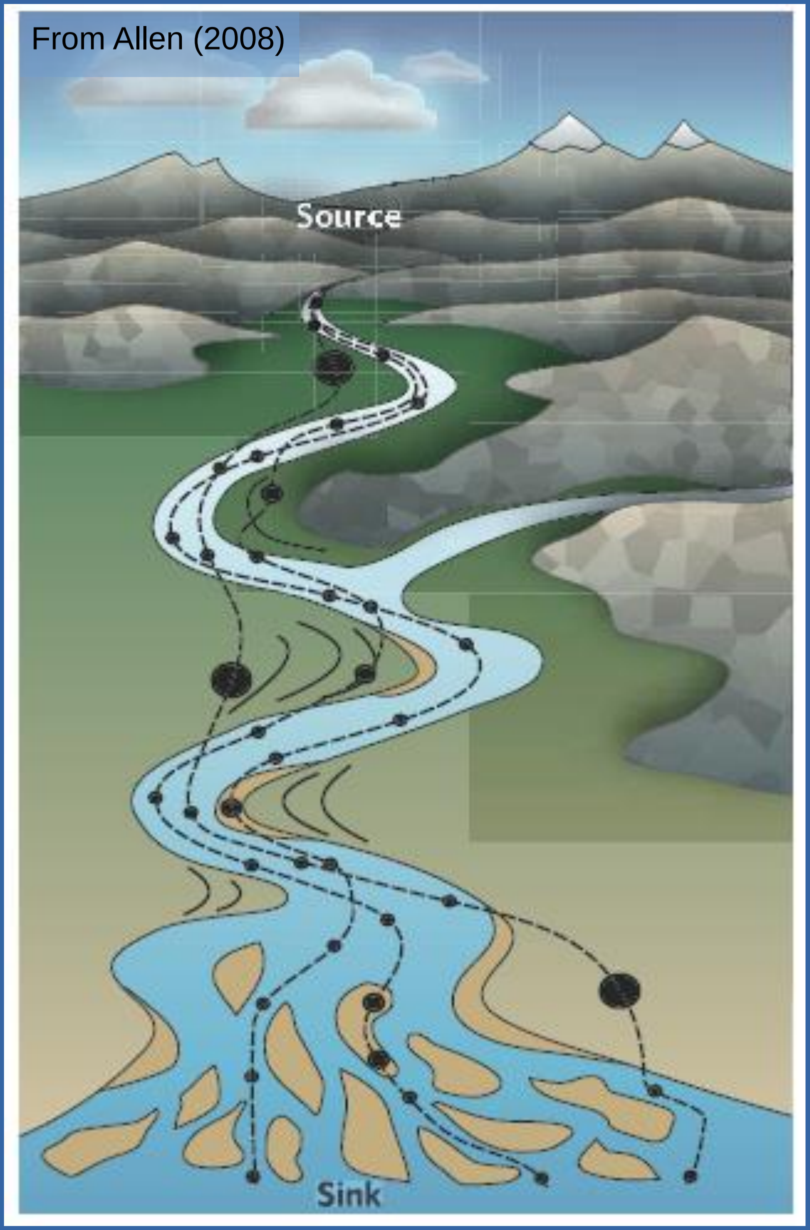
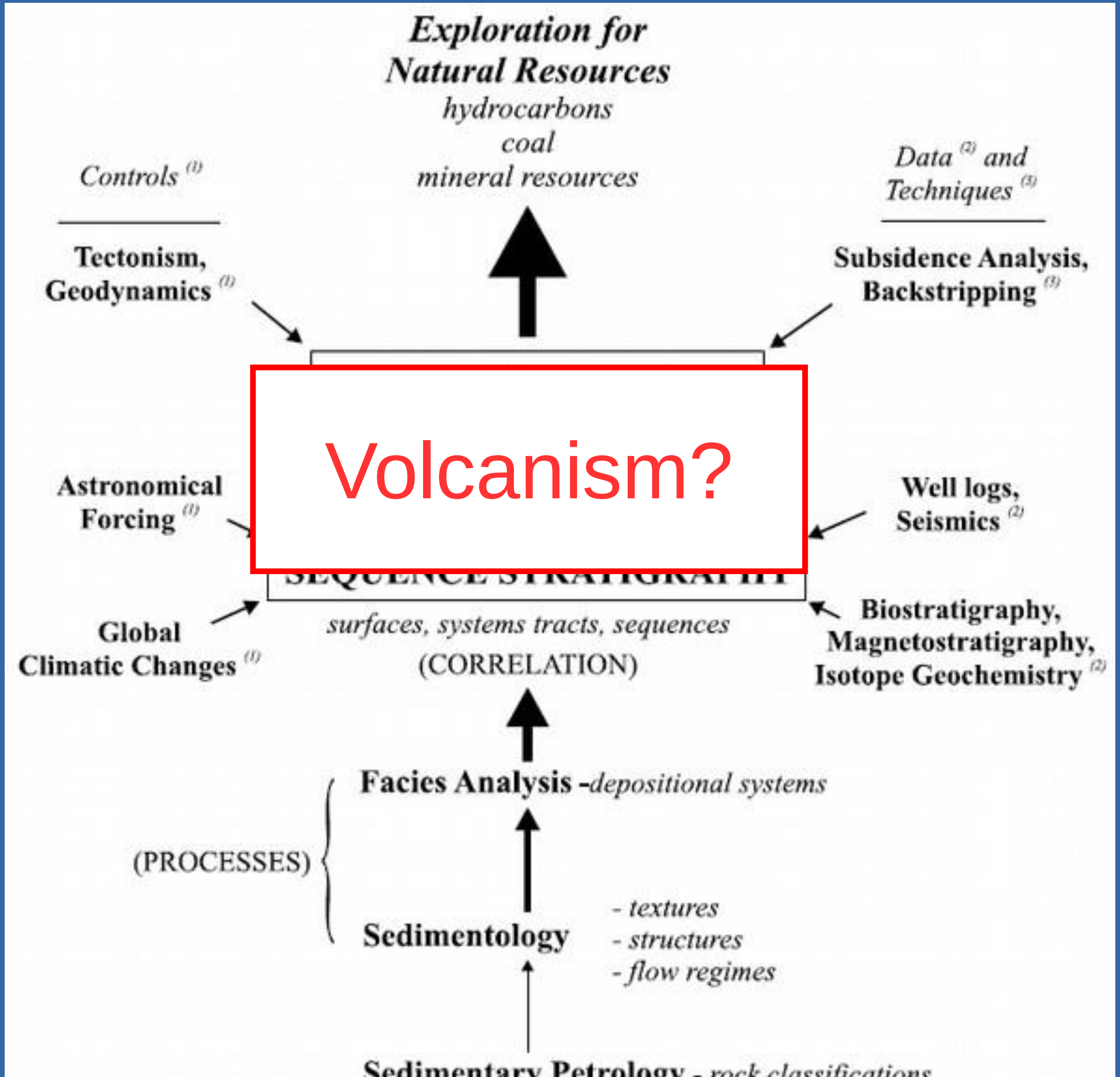


FIG. 1. Areas in which volcanics and/or volcaniclastics have been described in connection with hydrocarbon exploration or production. For the sake of clarity, only the first-named author of each reference is indicated.

Clastic Sedimentation

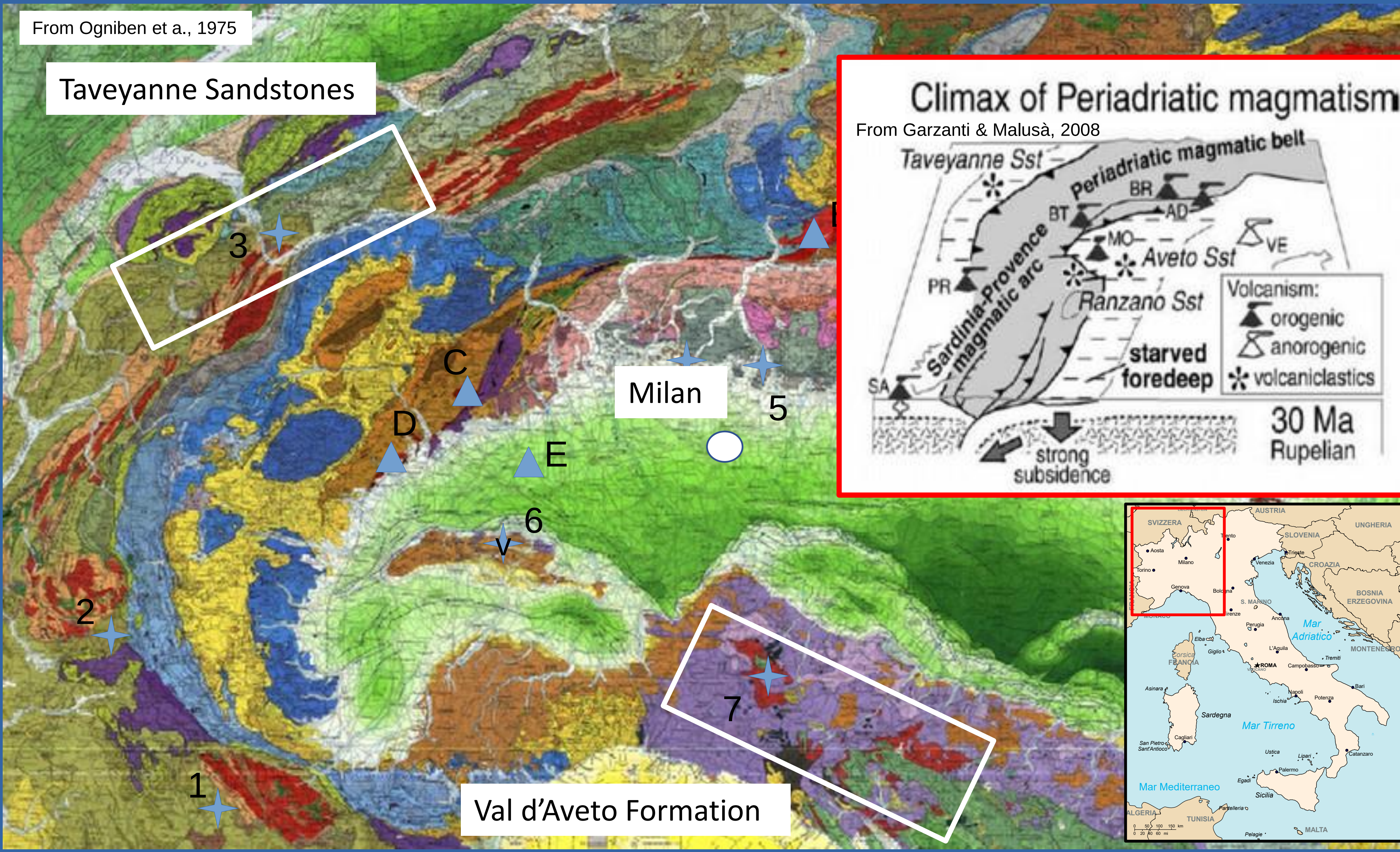


From Allen (2008)

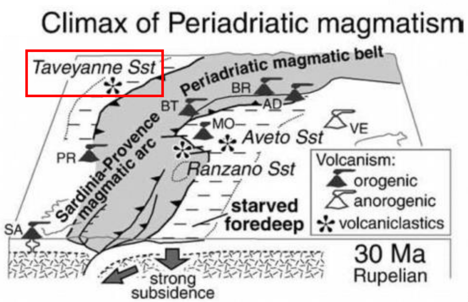


From Catuneanu (2002)

Geological setting:
Oligocene volcaniclastic deposits around the Alps

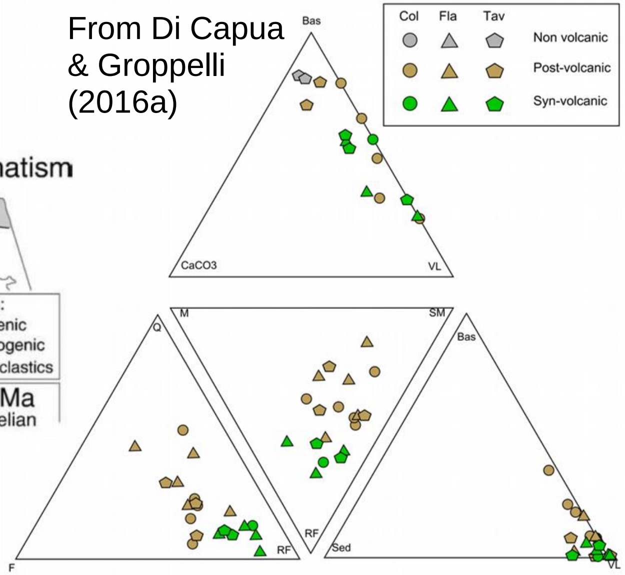


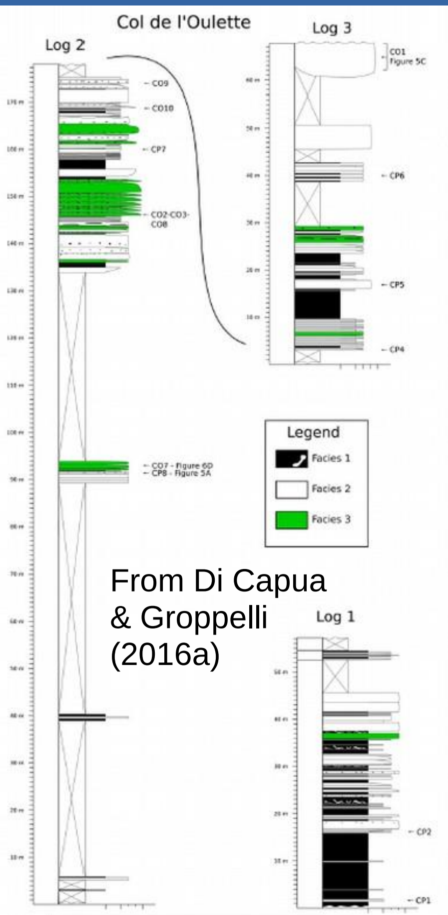
Taveyanne Sandstones (foreland basin)



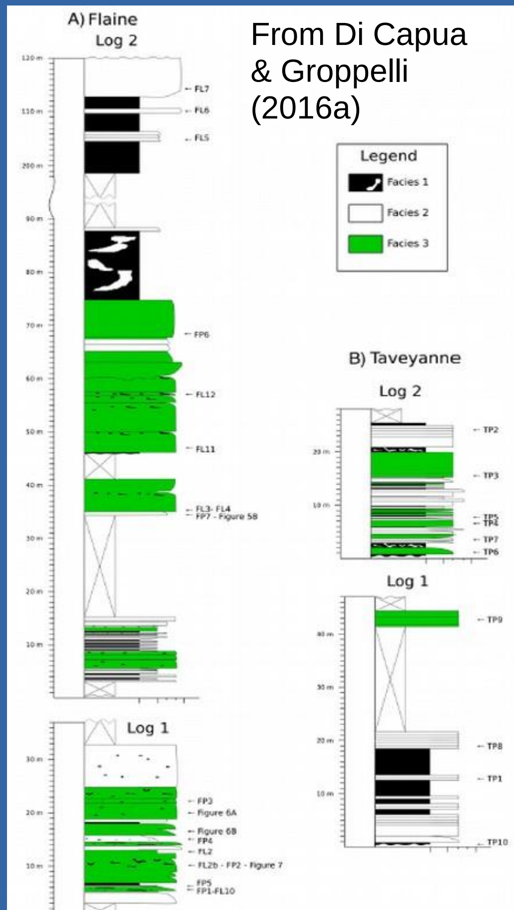
From Garzanti and Malusà (2008)

From Di Capua & Groppelli (2016a)



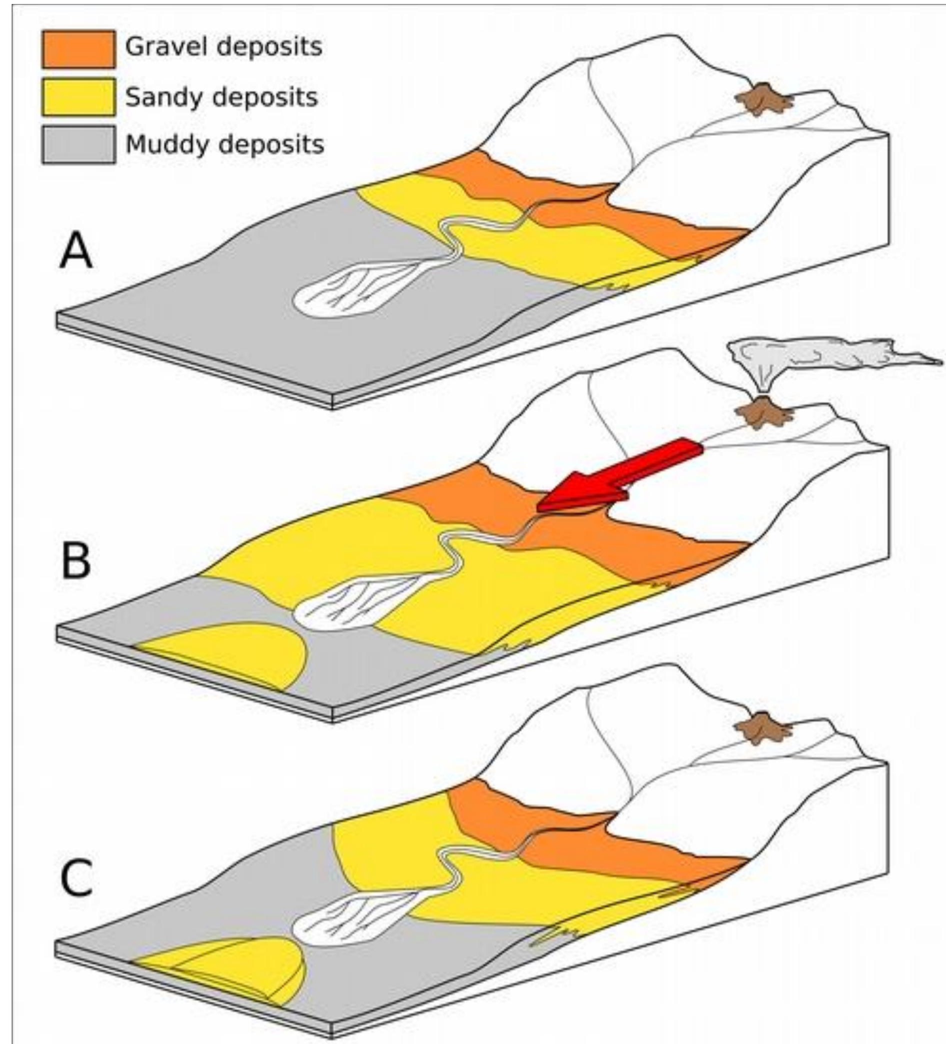


From Di Capua & Groppelli (2016a)



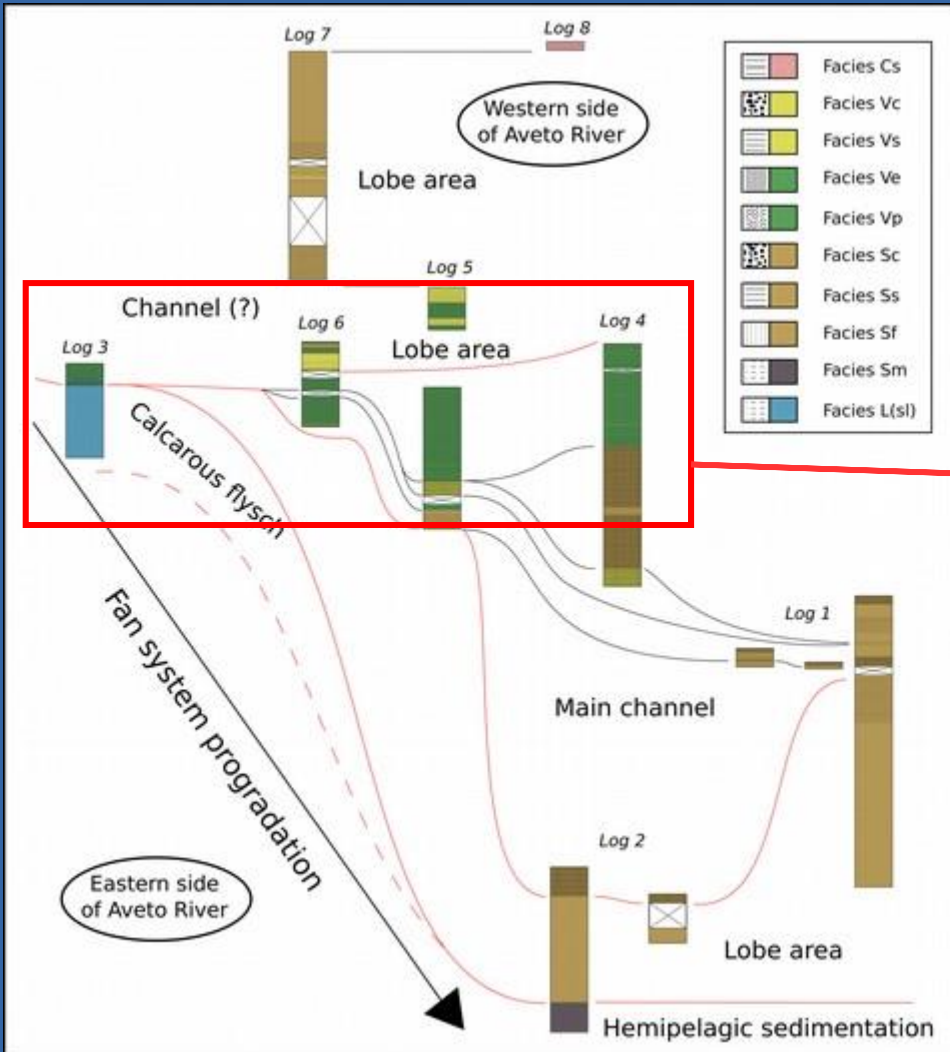
From Di Capua & Groppelli (2016a)

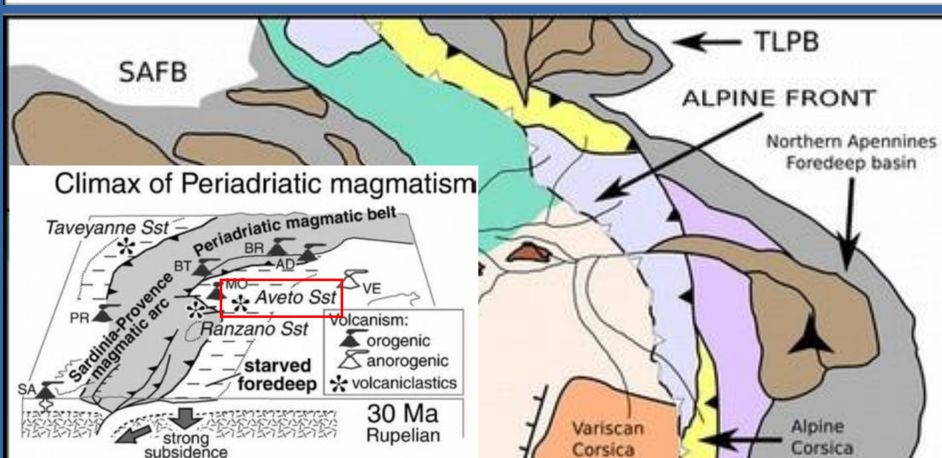
"Actualistic" sedimentary model

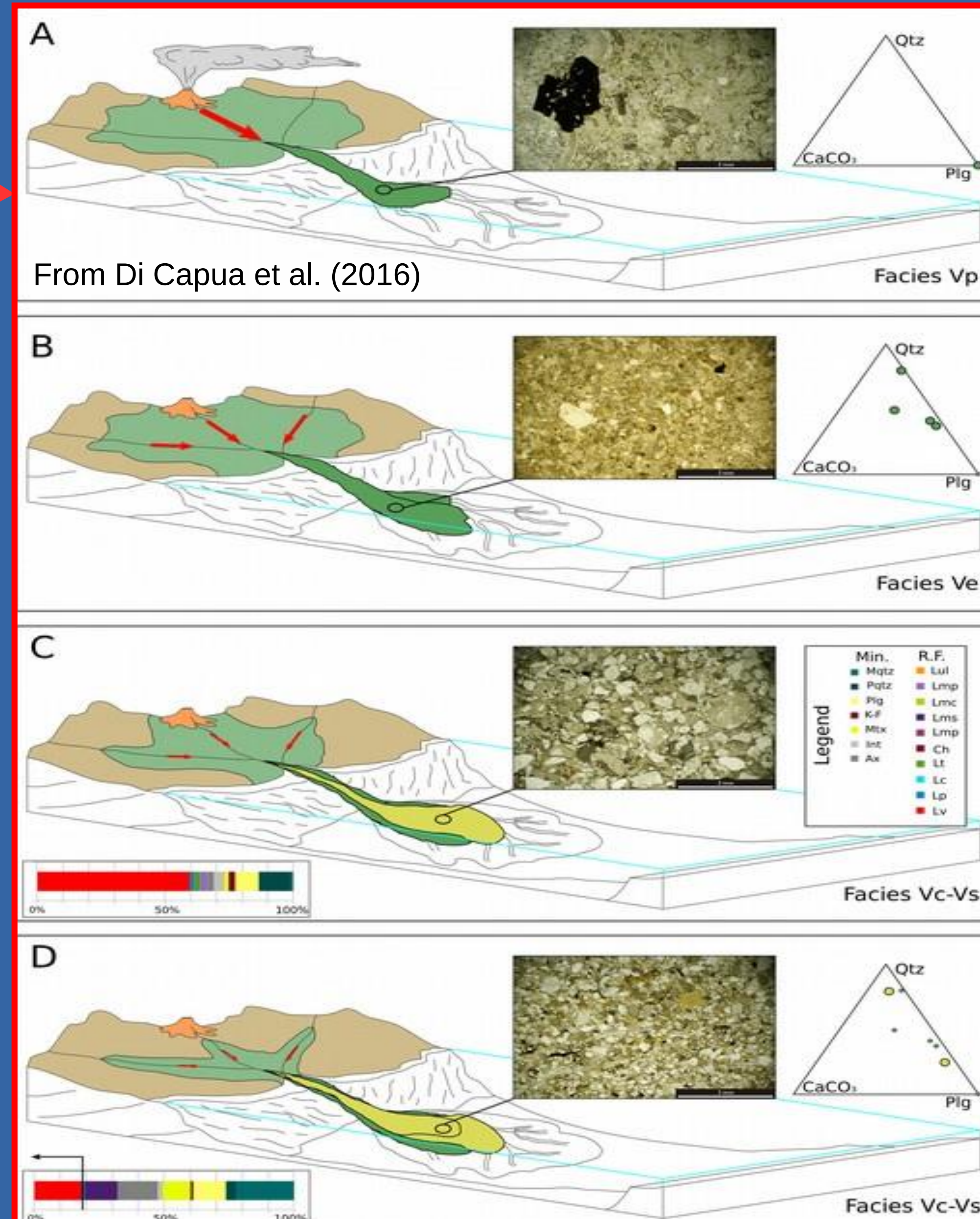


From Di Capua & Groppelli (2016a)

Val d'Aveto Formation (foredeep basin)







Approach and methodology

Multidisciplinary standardized workflow based on:

- *Intensive fieldwork activities* (geological mapping, structural analyses, **log measurements and correlations, facies analyses**)

- *Laboratory activities* (**petrography, sandstone point-counts, X-ray powder diffraction analyses, SEM-EDS, image analyses, effective porosity analysis,** paleomagnetism)

Classification of clastic deposits

CATEGORIES	DEFINITION	MAIN FEATURES	EFFECTIVE POROSITY
Non-volcanic deposits	Volcanic detritus may be present as particles eroded from ancient volcanic sequences, so volcanism had no influence on sedimentation	Lack of pseudomatrix; volcaniclastic detritus (if present) = palaeovolcanic fragments (sensu Critelli & Ingersoll, 1995)	From 1,1 to 8,8% Function of hydraulic sorting
Syn-volcanic deposits • **Syn-eruptive** • **Post-eruptive**	Volcanic detritus is directly provided during or soon after a volcanic event	Porphyritic to eutaxitic textures; abundance of pseudomatrix; volcaniclastic detritus = neovolcanic fragments (sensu Critelli & Ingersoll, 1995)	From 1,7 to 11,6 % Function of volcanic event
Post-volcanic deposits	Volcanic detritus is supplied by the resedimentation of dispersed, unconsolidated volcanic detritus, so the progressive lithification of onland volcaniclastic deposits tends to proportionally decrease the amounts of volcanic particles in the deposits	Lack of pseudomatrix; volcaniclastic detritus = neovolcanic + palaeovolcanic fragments (sensu Critelli & Ingersoll, 1995)	From 1,8 to 11,4% Function of hydraulic sorting

Based on the temporal relationship between volcanism and sedimentation

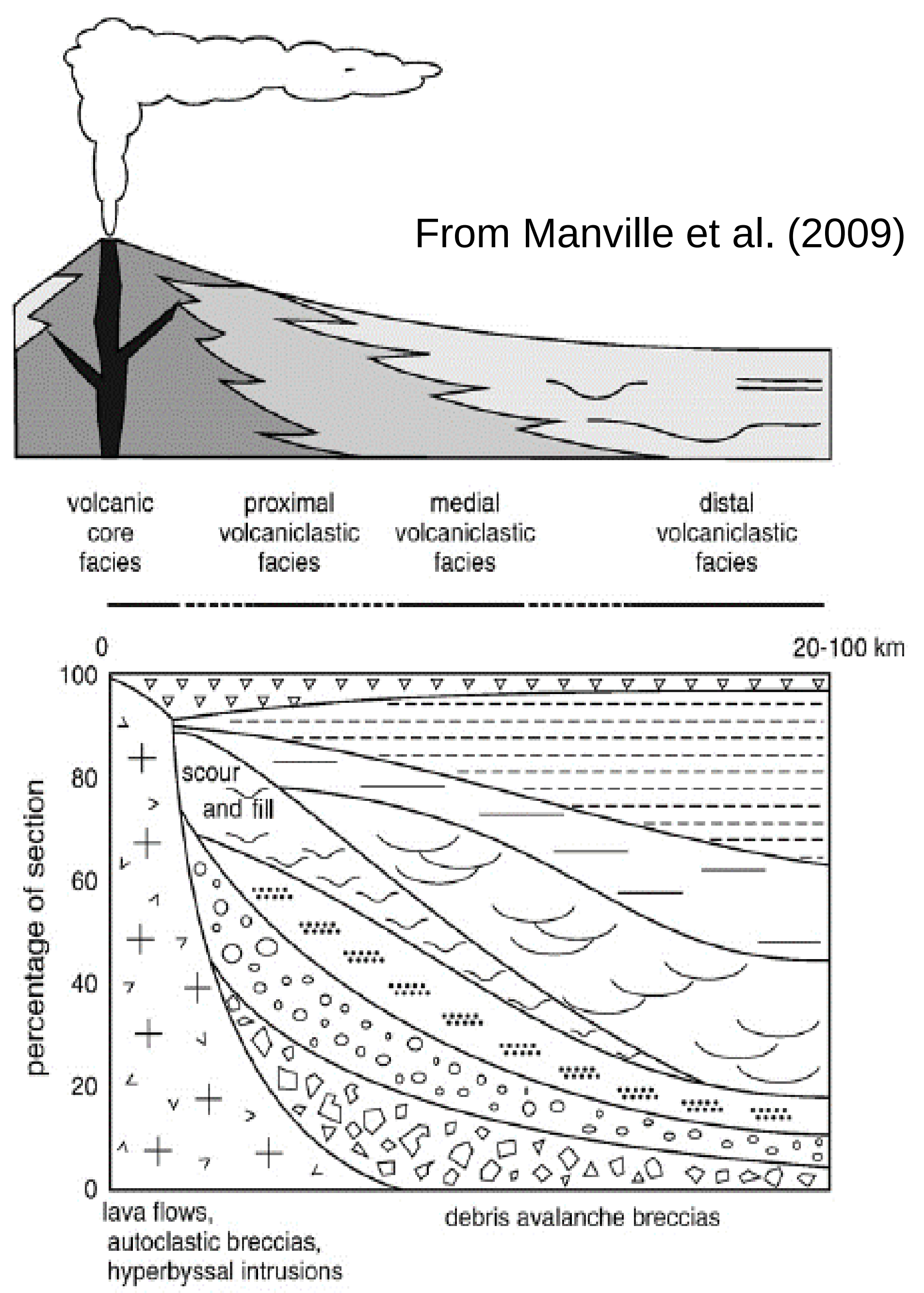
Syn-volcanic deposits

Features varying on the base of: 1) the type of explosive volcanic event and 2) the environmental conditions

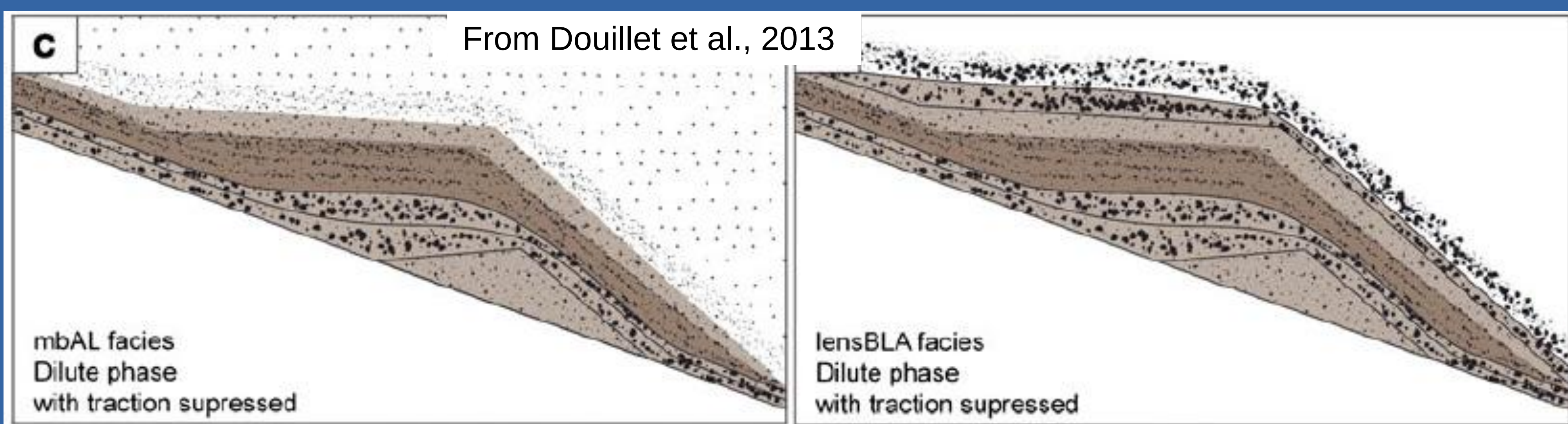
<u>Grain-size distribution</u> = function of the physical behavior of the eruptive event

Detritus produced and istantaneously transported for tens to hundreds of kilometers

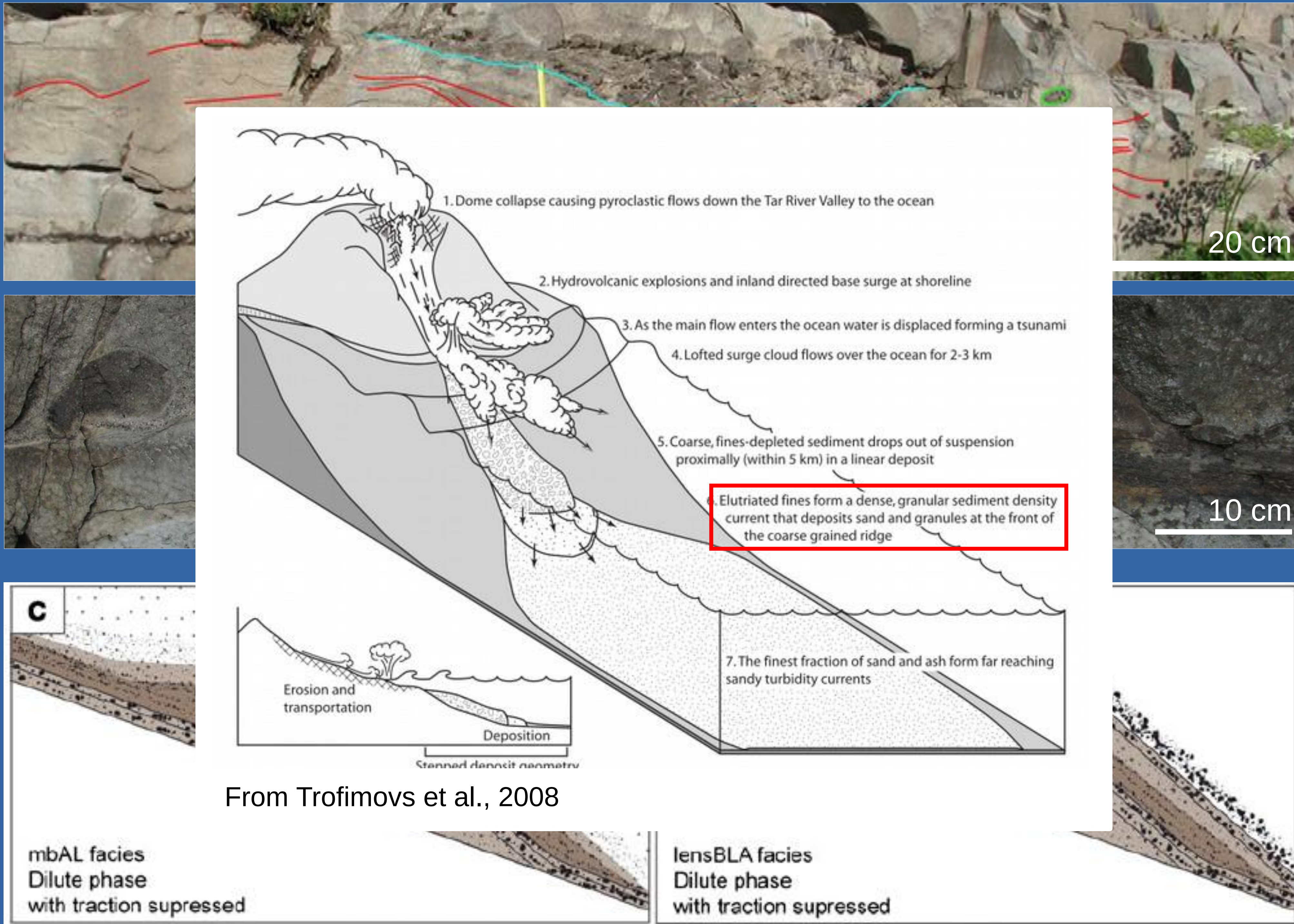
<u>Syn-Volcanic Syn-eruptive or Post-eruptive deposits</u>



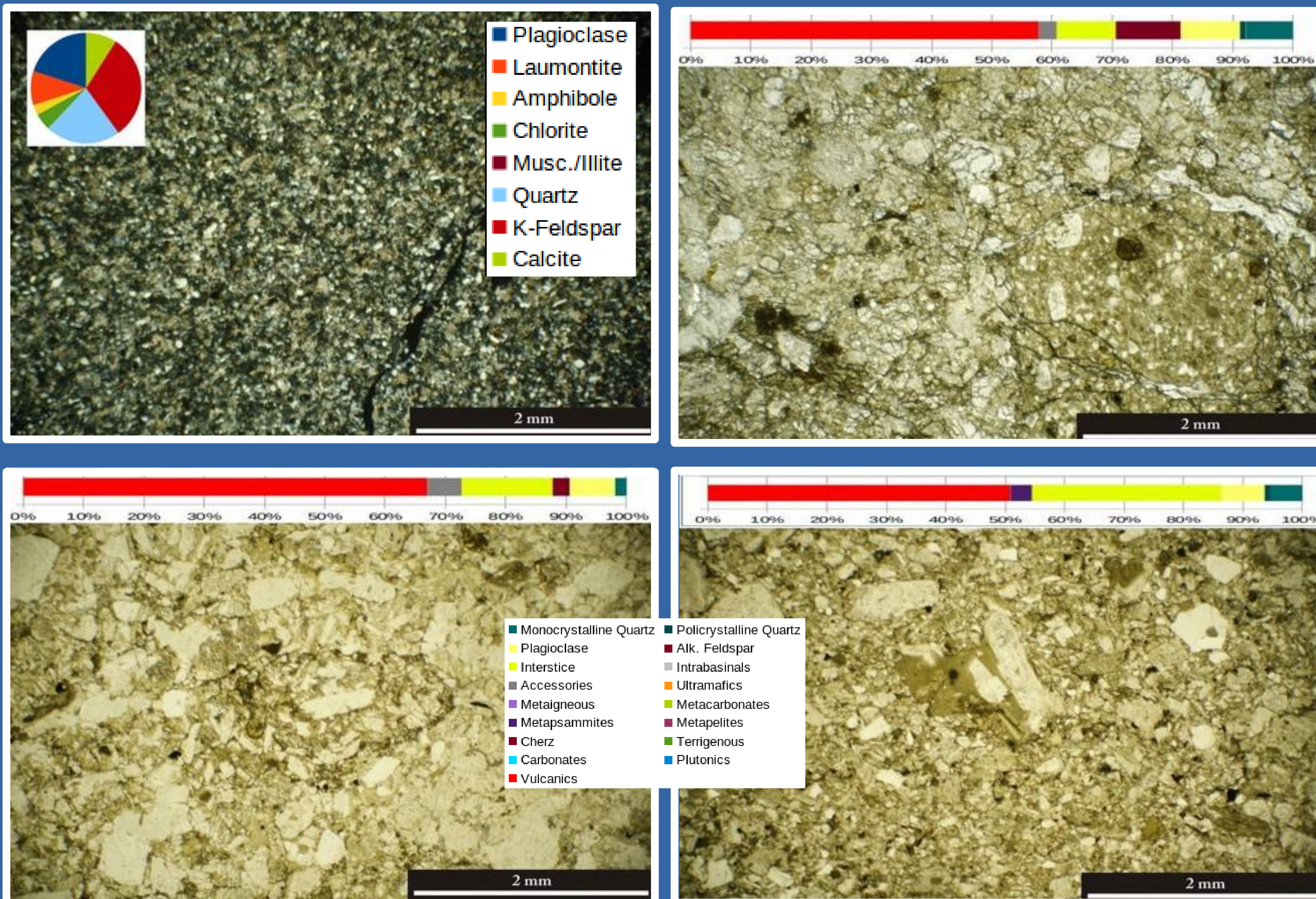
Syn-volcanic syn-eruptive deposits: disaggregated PDCs



From Douillet et al., 2013



From Trofimovs et al., 2008


Plagioclase
Laumontite
Amphibole
Chlorite
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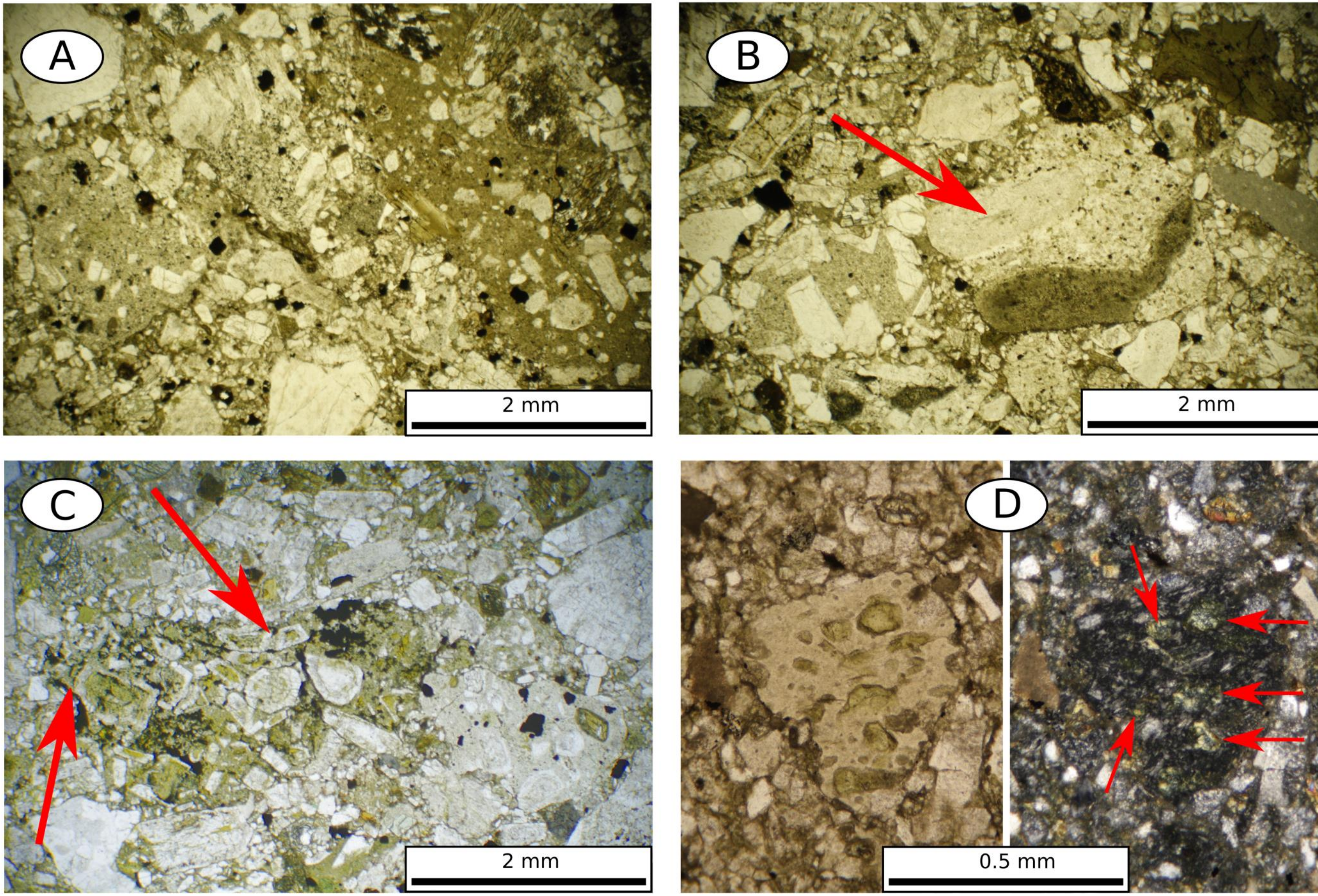
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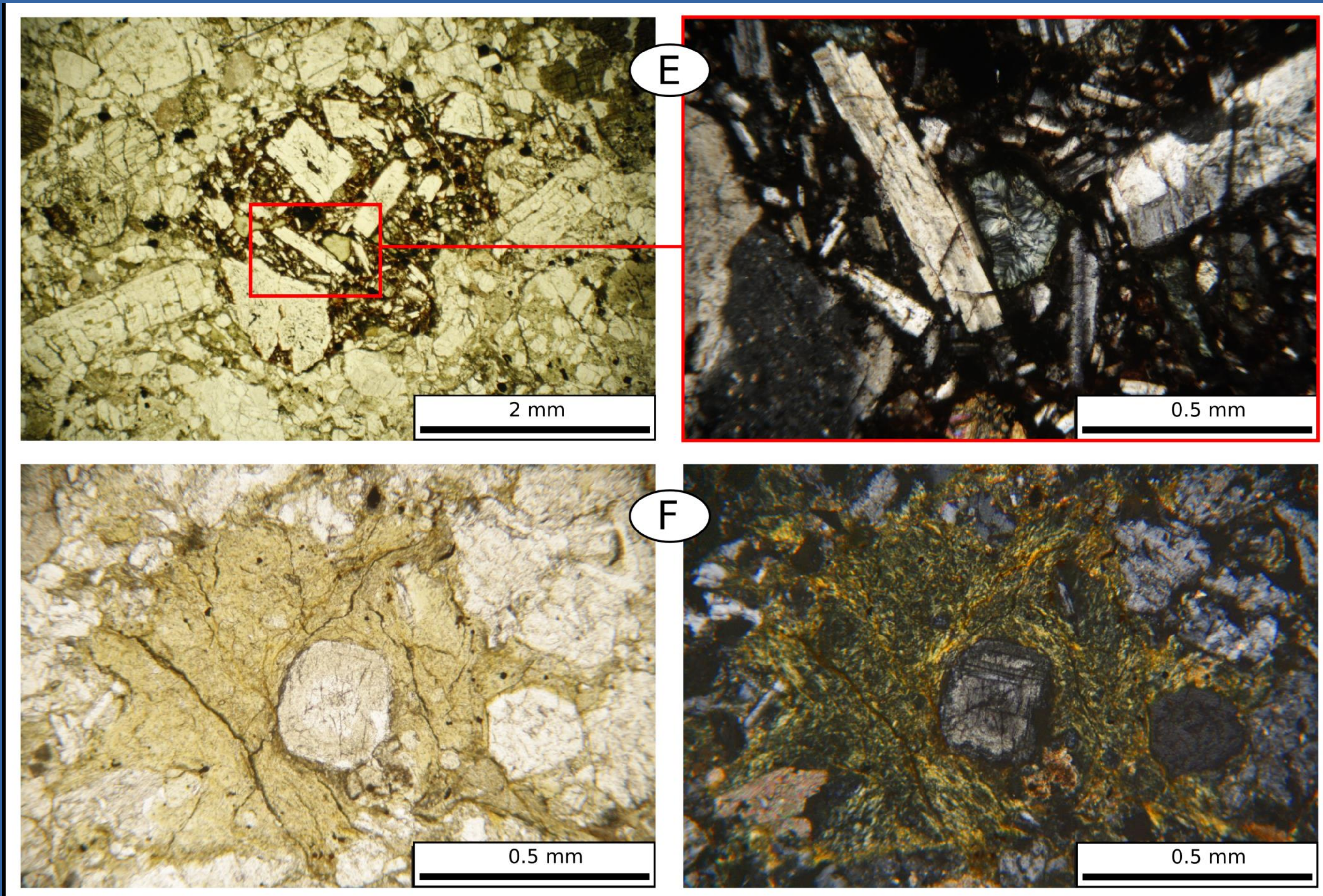
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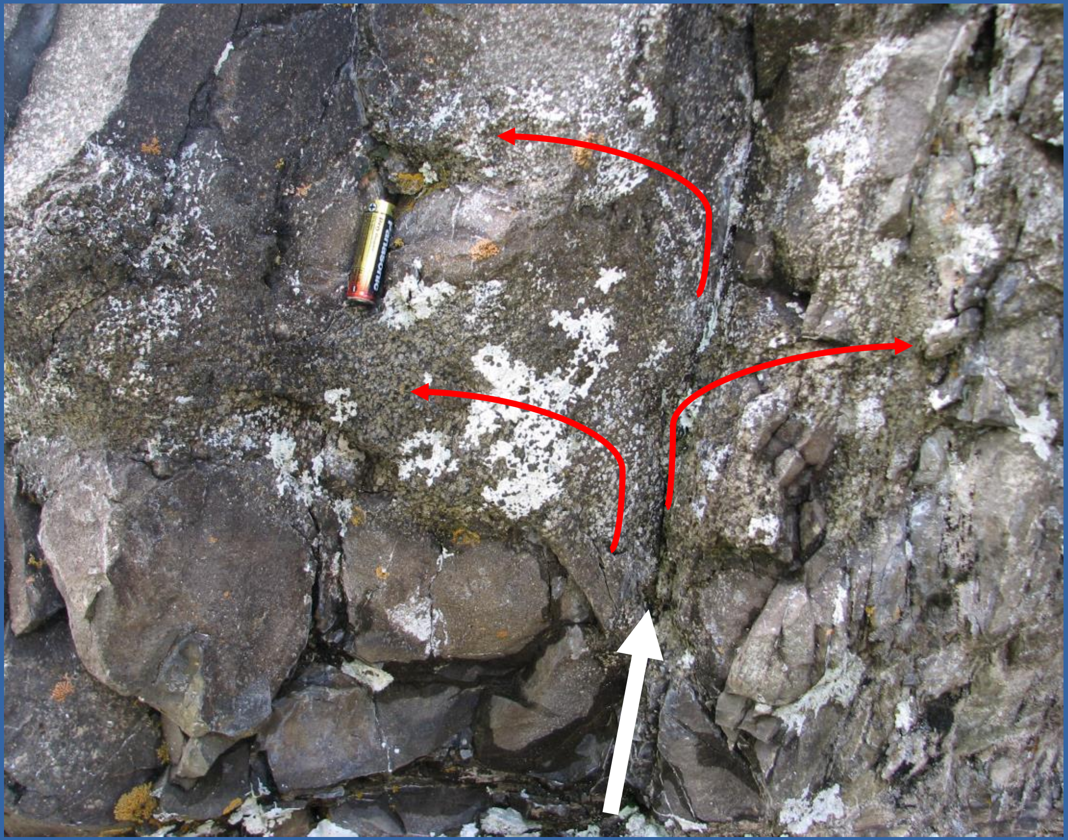
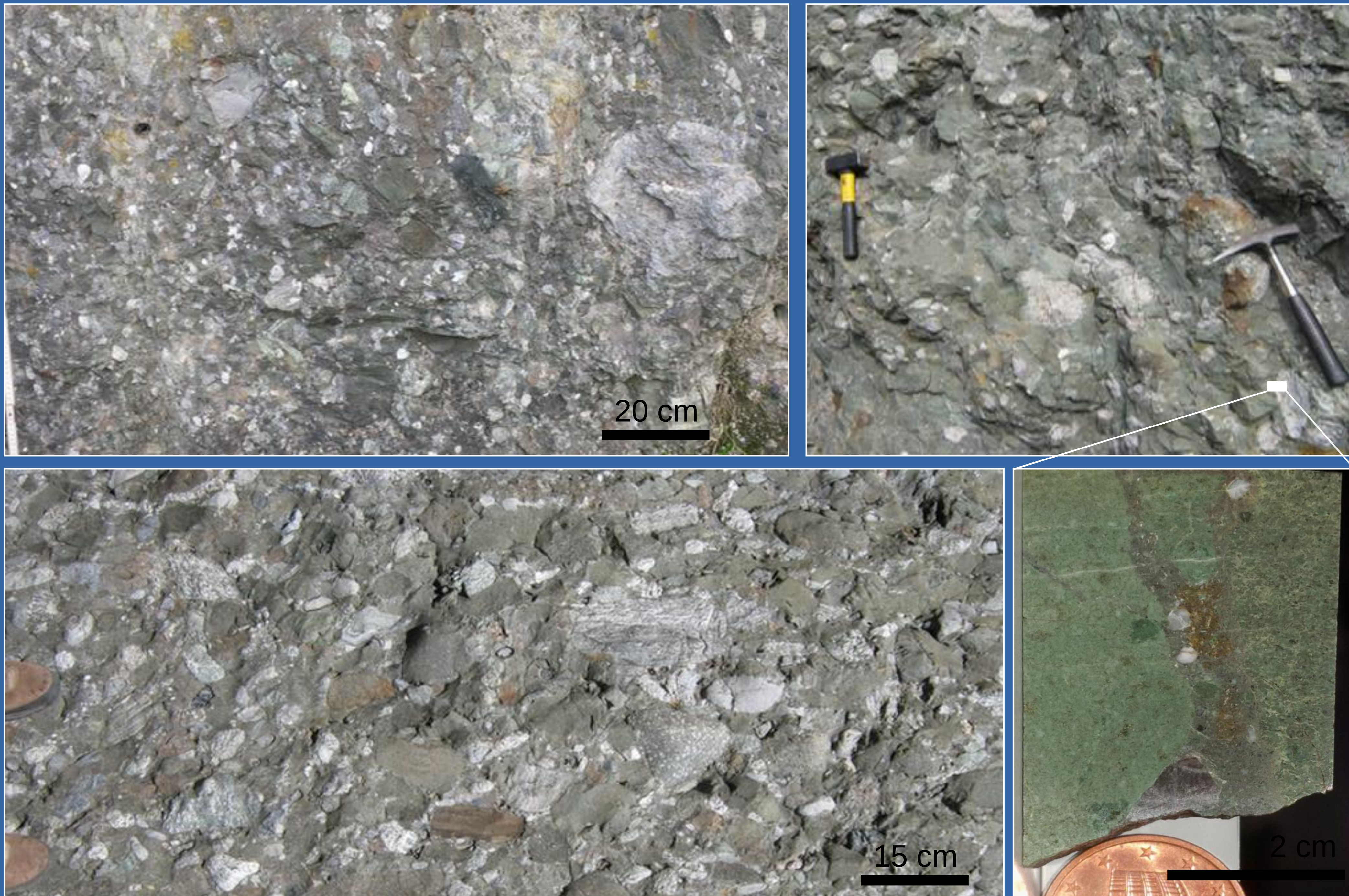
Laumontite in Taveyanne Sandstone



Laumontite cement creating «bee-structures» (Ruffini et al., 1995), substituting glass and plagioclase.

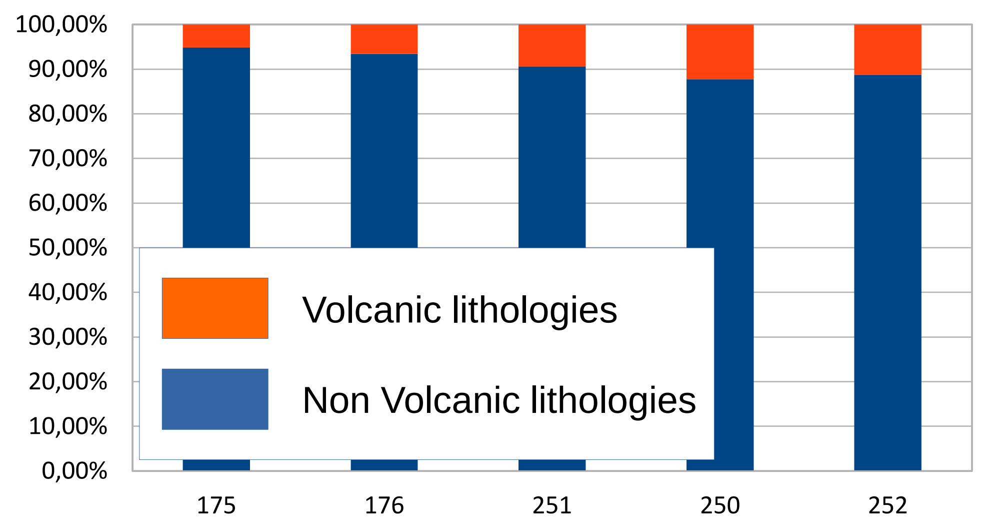
Preservation of primary porosity (e.g., Zhu et al., 2014)

Syn-volcanic syn-eruptive deposits: preserved PDCs

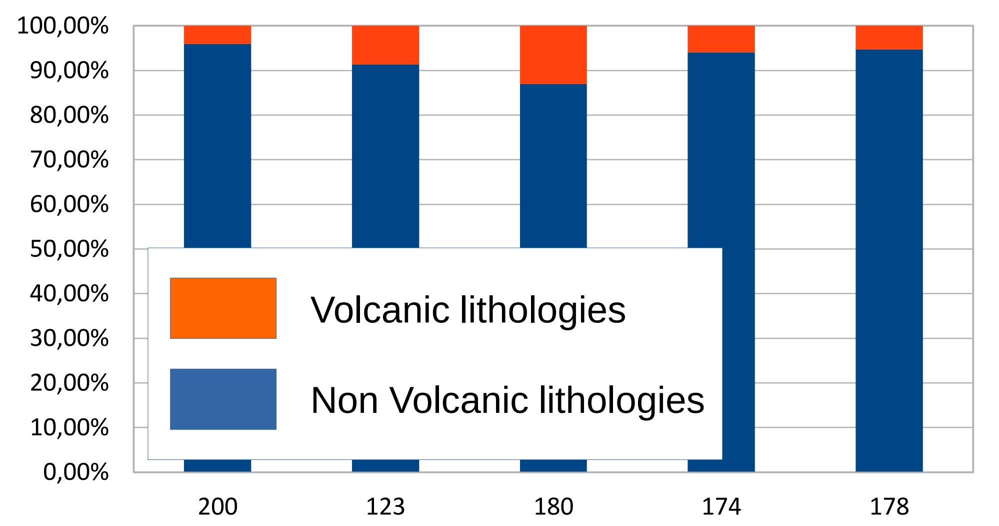


Gravel-size detritus

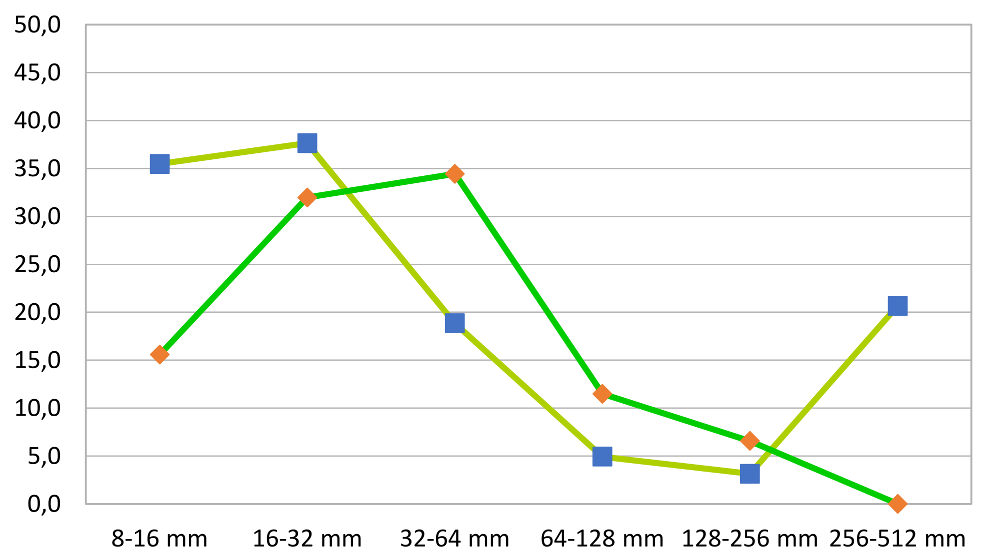
Syn-volcanic deposits

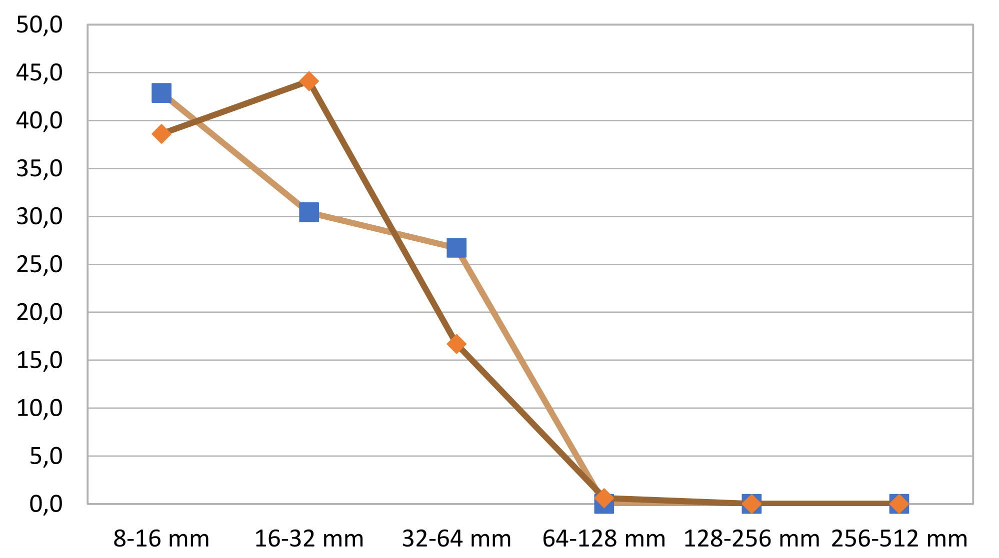


Non-volcanic deposits



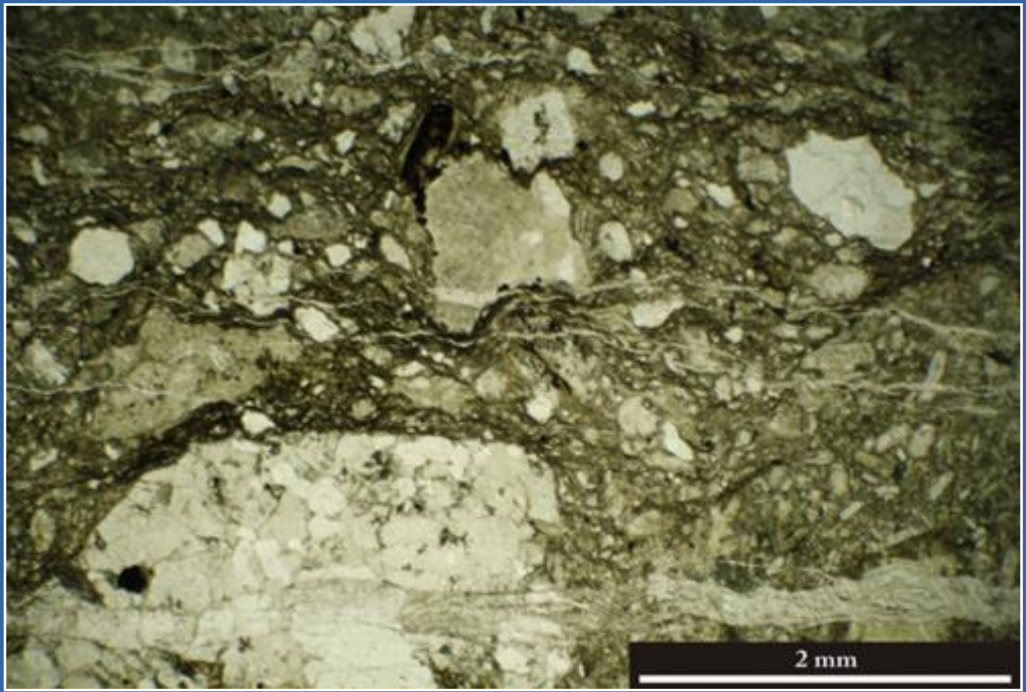
Lithological association of the gravel-size detritus, resulting from clast counts in the field

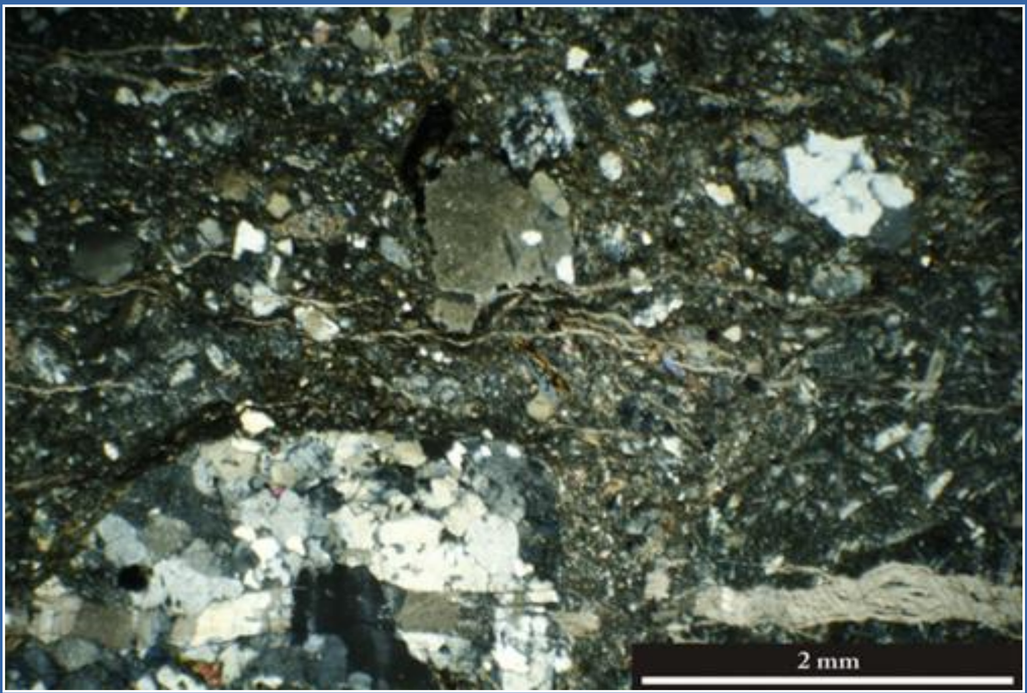


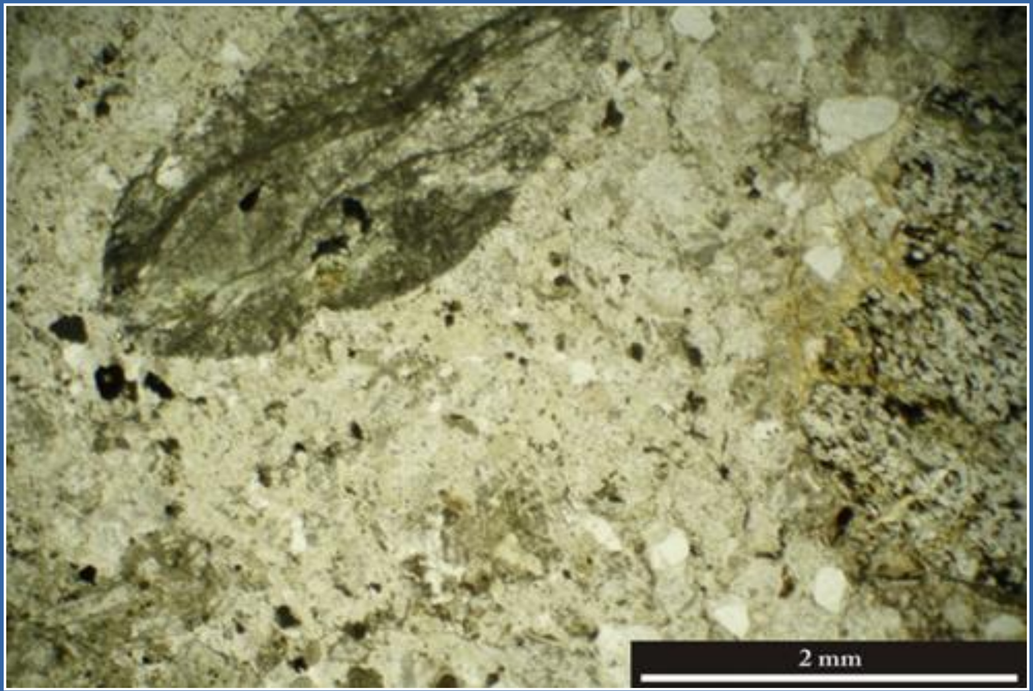


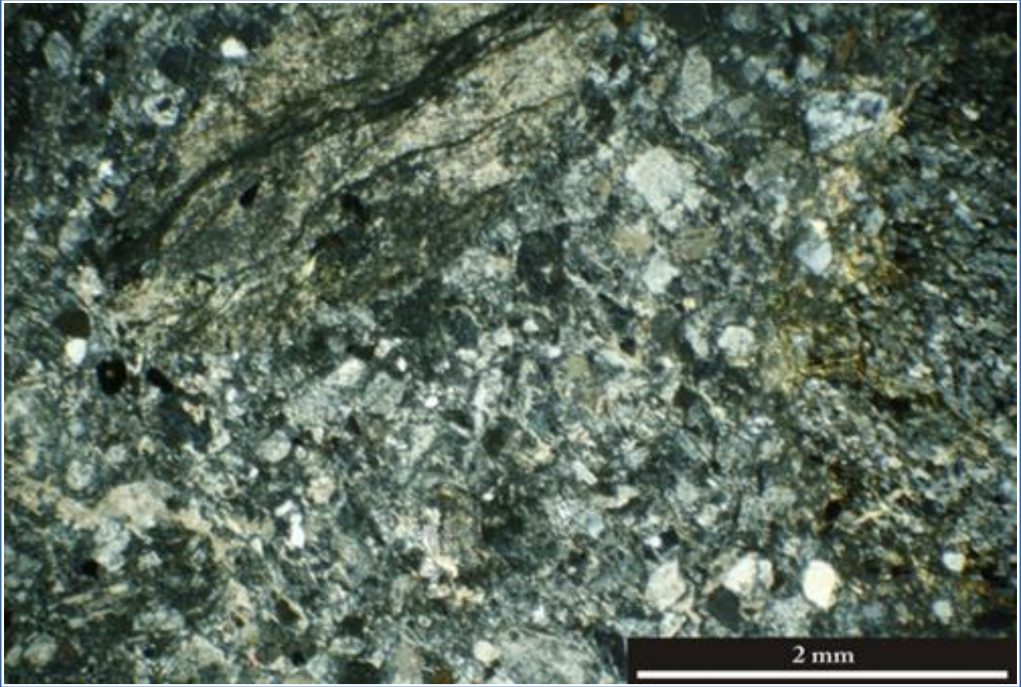
Grain size distribution of the gravel-size detritus resulting from image analyses

Syn-volcanic syn-eruptive deposits: preserved PDCs

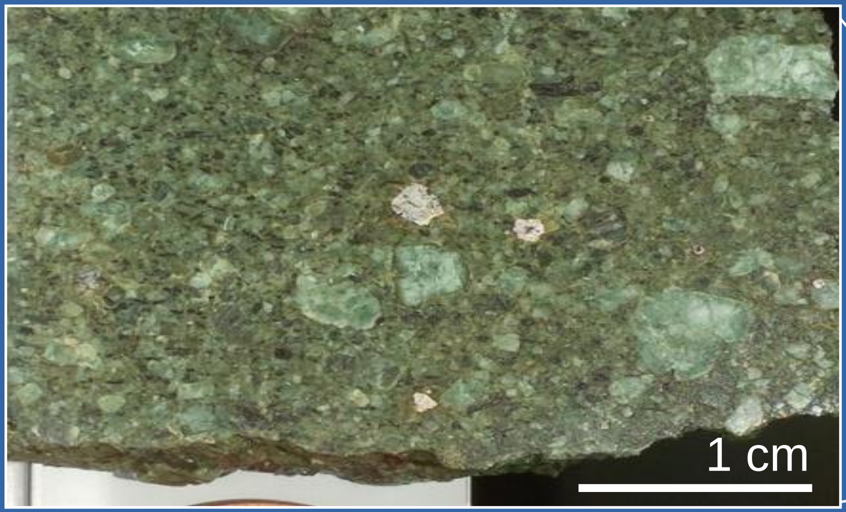


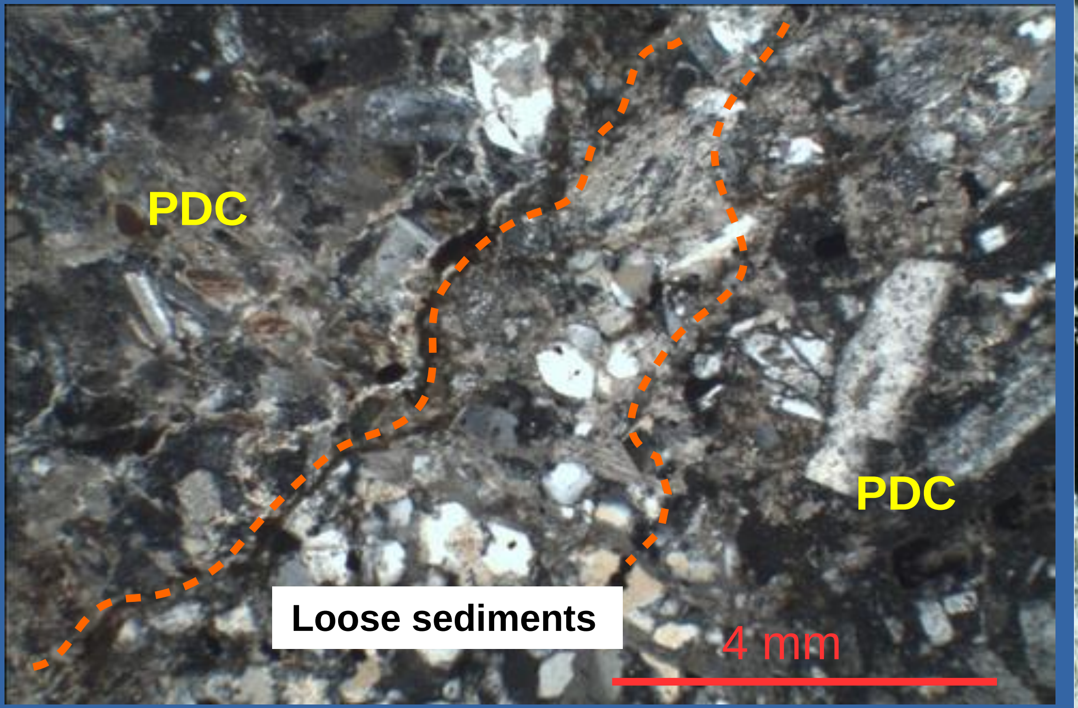


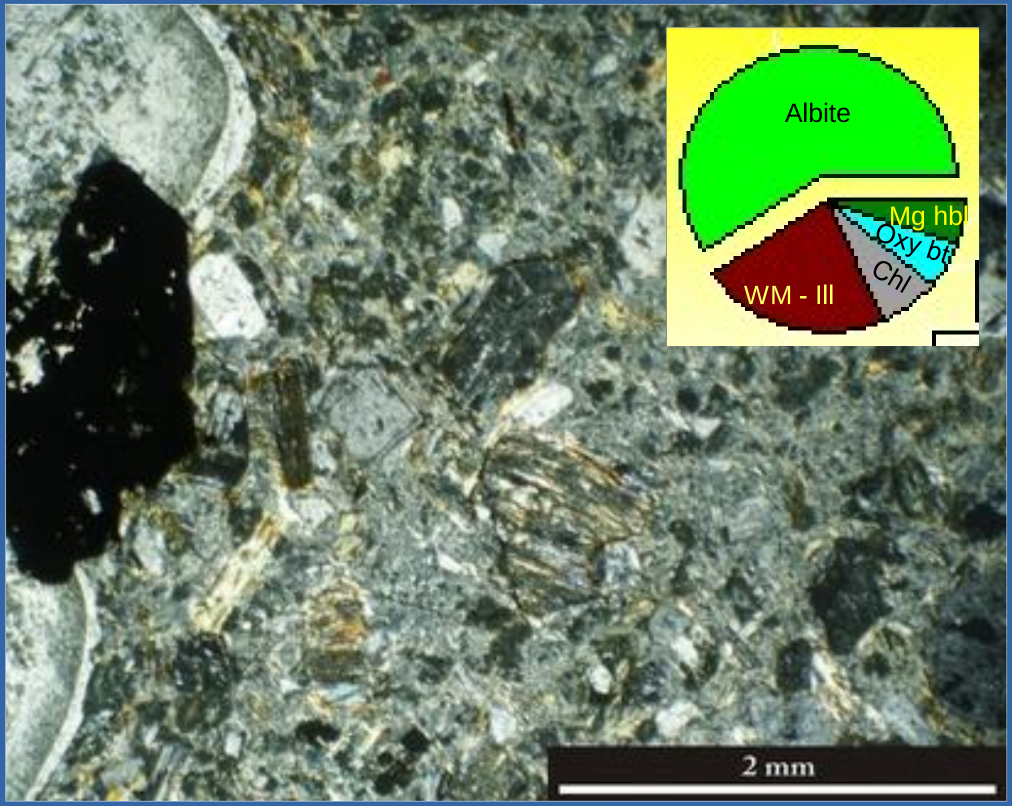




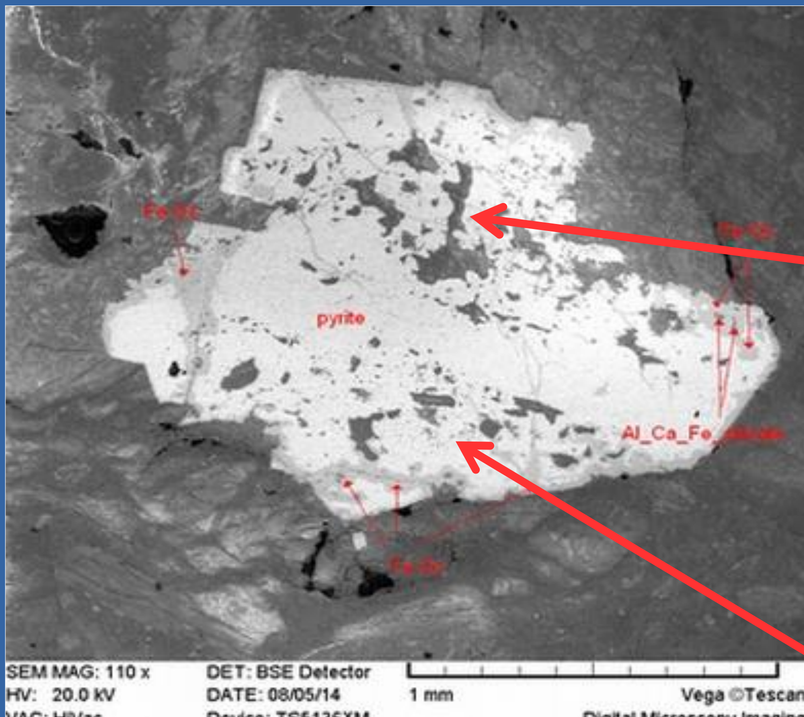
Syn-volcanic syn-eruptive deposits: preserved PDCs

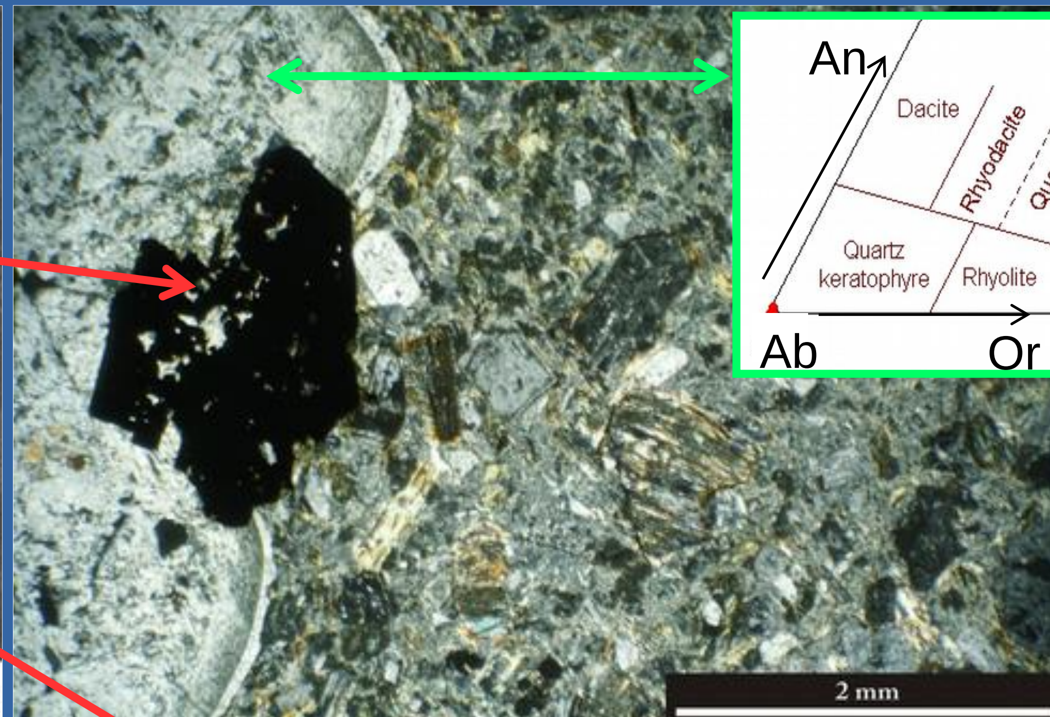






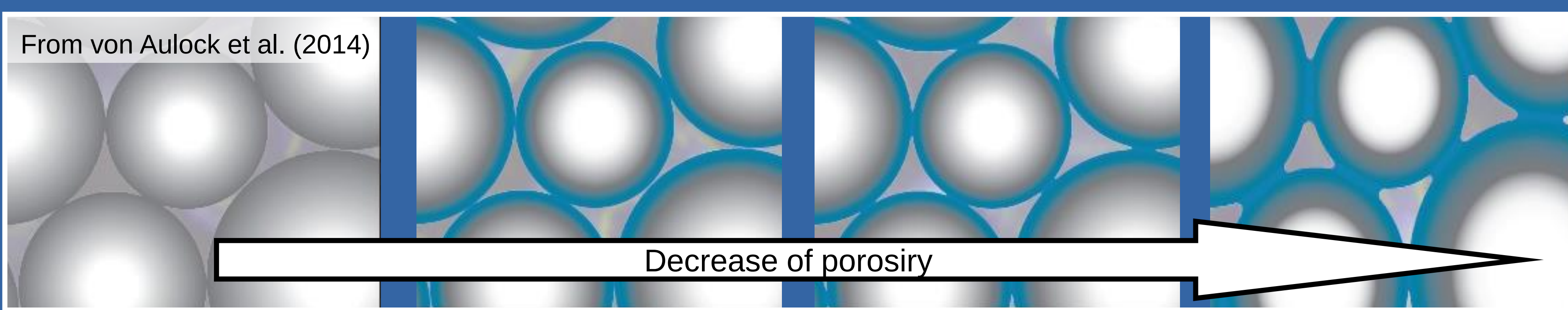
Syn-volcanic syn-eruptive deposits: preserved PDC





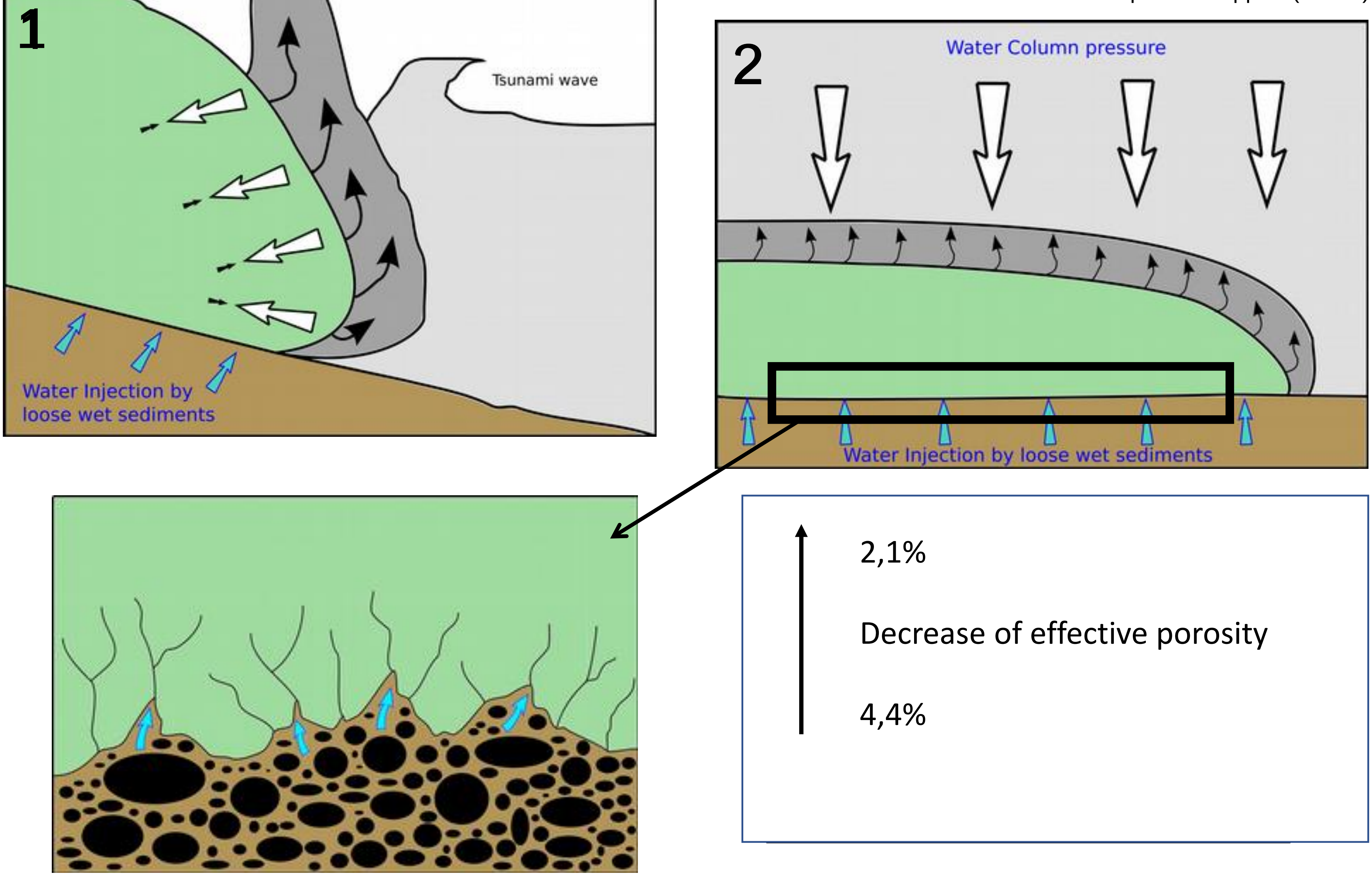
Type	Surface *1	Coexist. Phases	Grain Size	Habit	Faces *2	Habit Type *3	Abundance	Temperature	Experimets *4	Remarks
Pyrite C1	S°	S°	<1µ - < 50µ	cubo - octa	100/111	1, 2, 19	very mi[illegible]	250 - 350	II, IV	growth on top of sulfur droplet surface
Pyrite C2	S°	S°	<1µ - < 50µ	pyritohedral	210/100/111	4	> Py C1	300 - 350	II	growth between two sulfur droplets
Pyrite C3	S°, Po	S°, Po, Py A	1µ - 10µ	pyritohedral	210/100/111	4, 7	Py C1< Py C3< Py C2	300 - 350	II	growth between Py A and sulfur droplets
Pyrite D	---	hematite	< 1µ - 0.3 mm	pyritohedral	210/100/111	4, 7, 6	> Py B1	250 - 350	II, IV	formation of clusters

From Graham and Ohmoto, 1994

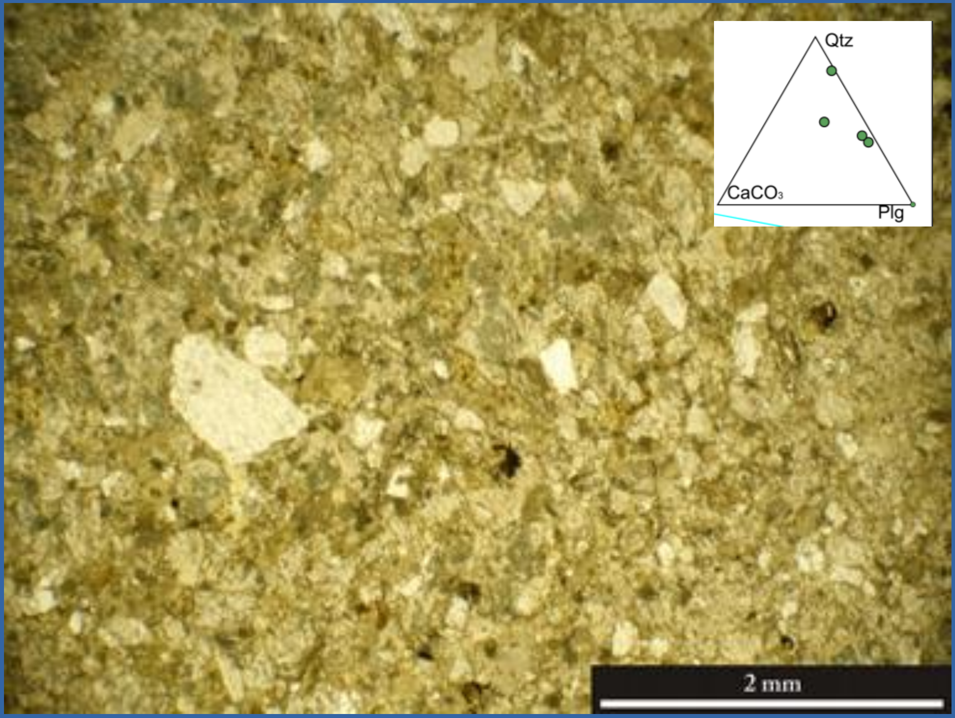


Syn-volcanic syn-eruptive deposits: preserved PDC

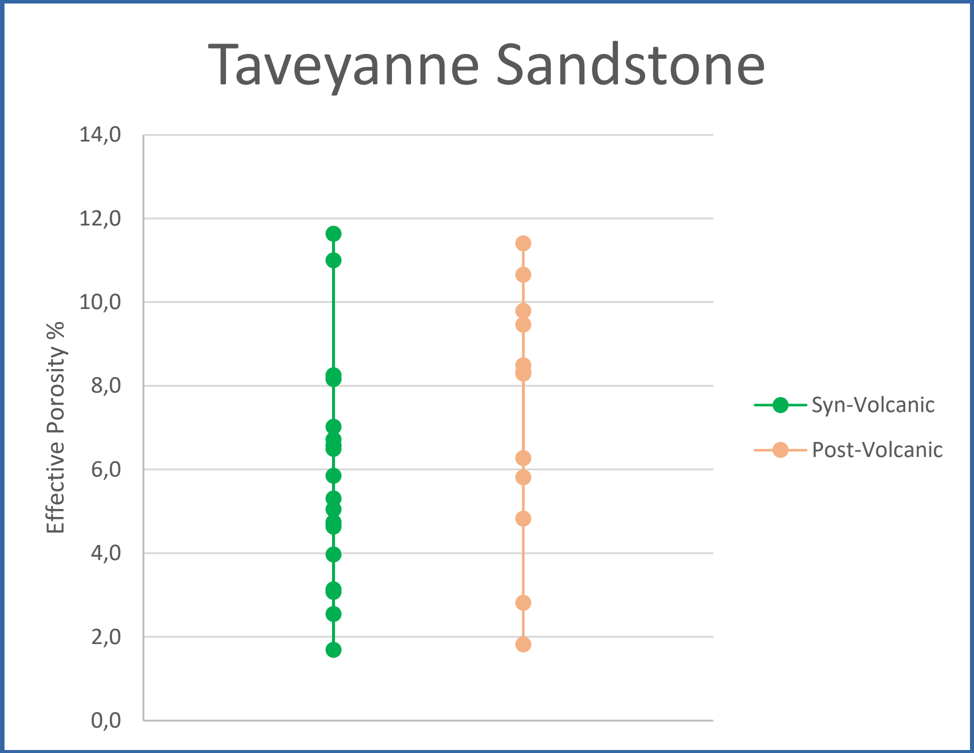
From Di Capua & Groppelli (2016b)

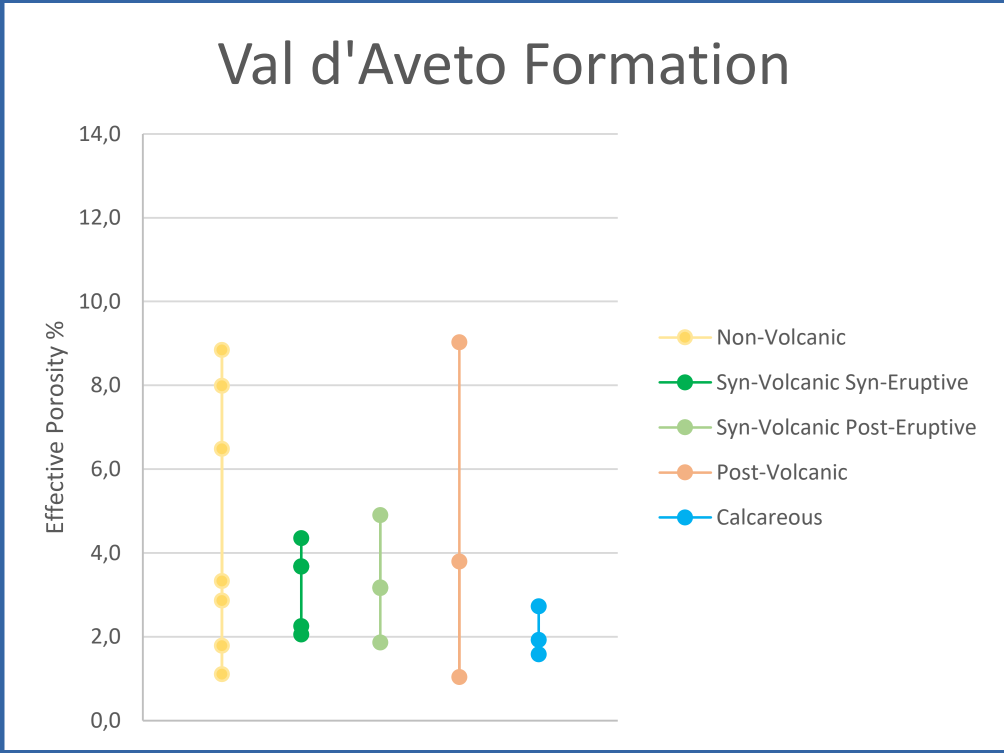


Syn-volcanic post-eruptive deposits



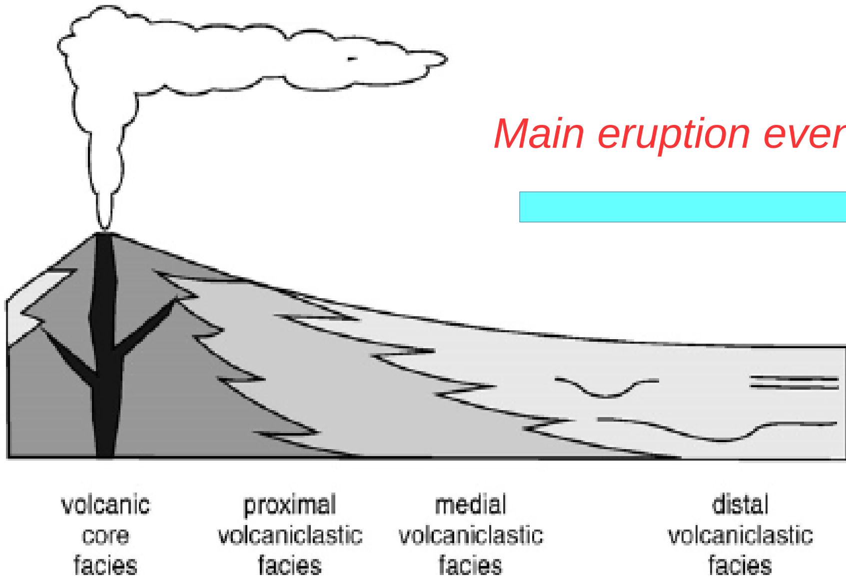
Effective porosity



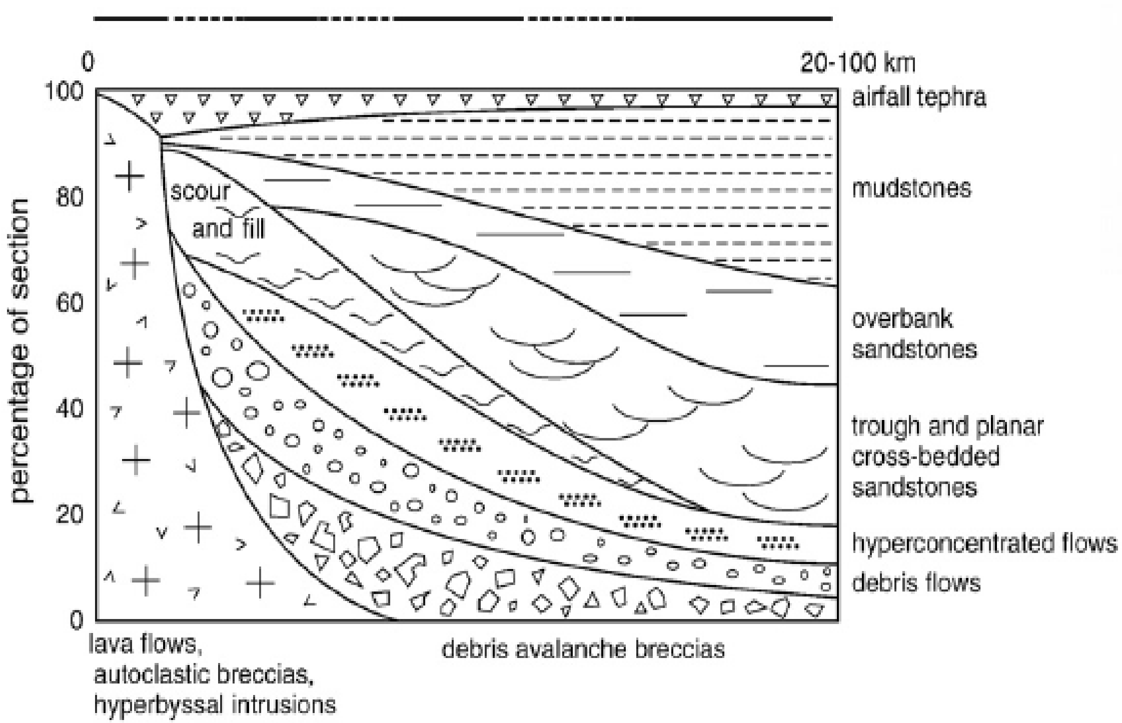


Function of the behavior of eruptive event

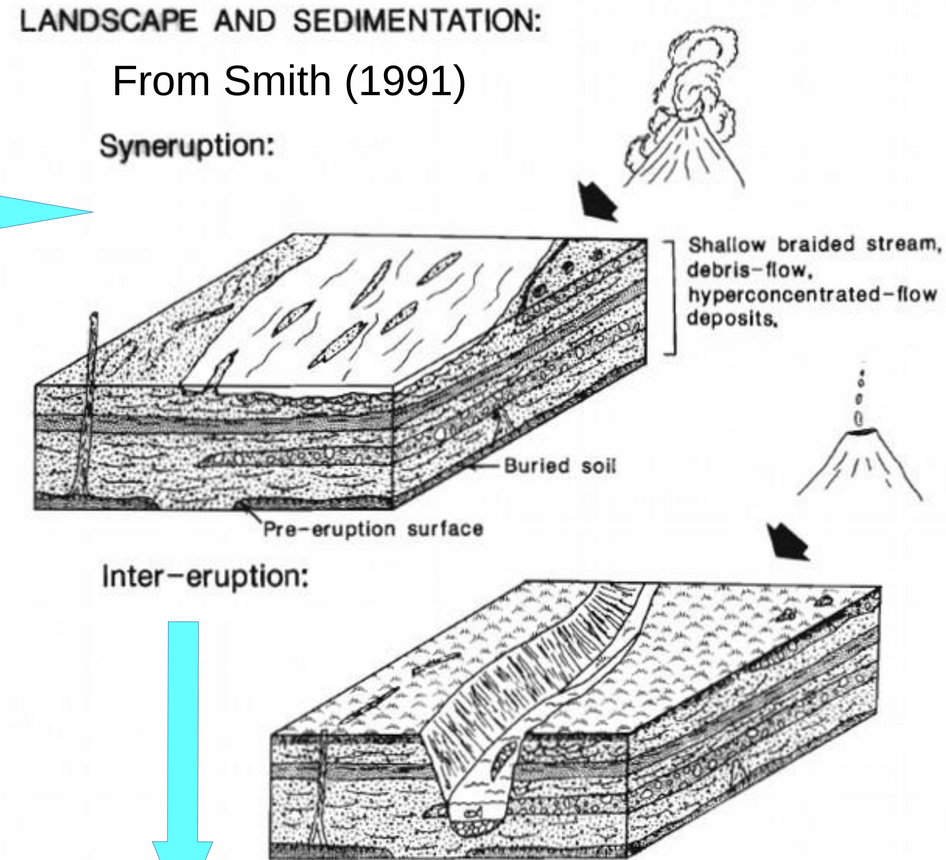
Post-depositional history (diagenesis)



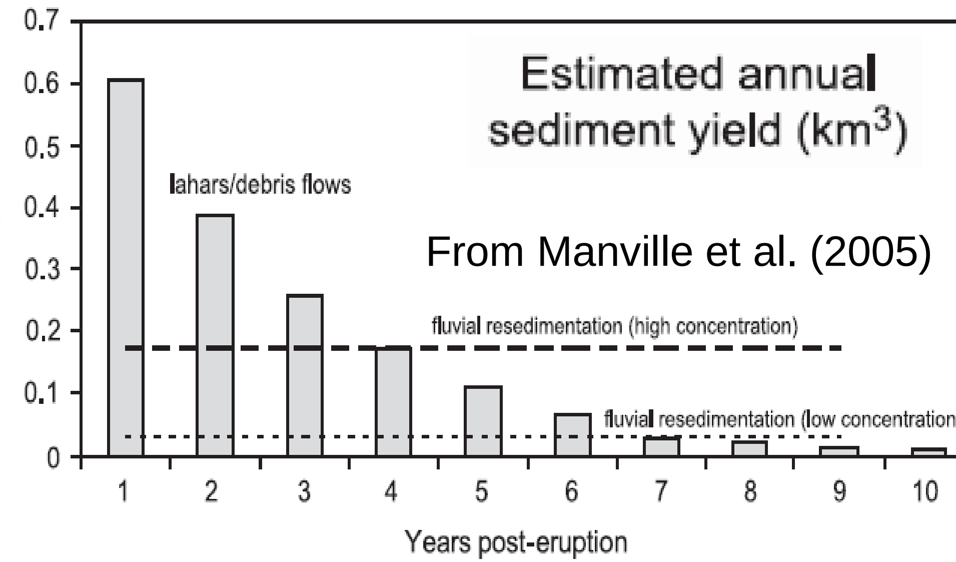
Main eruption event



From Manville et al. (2009)

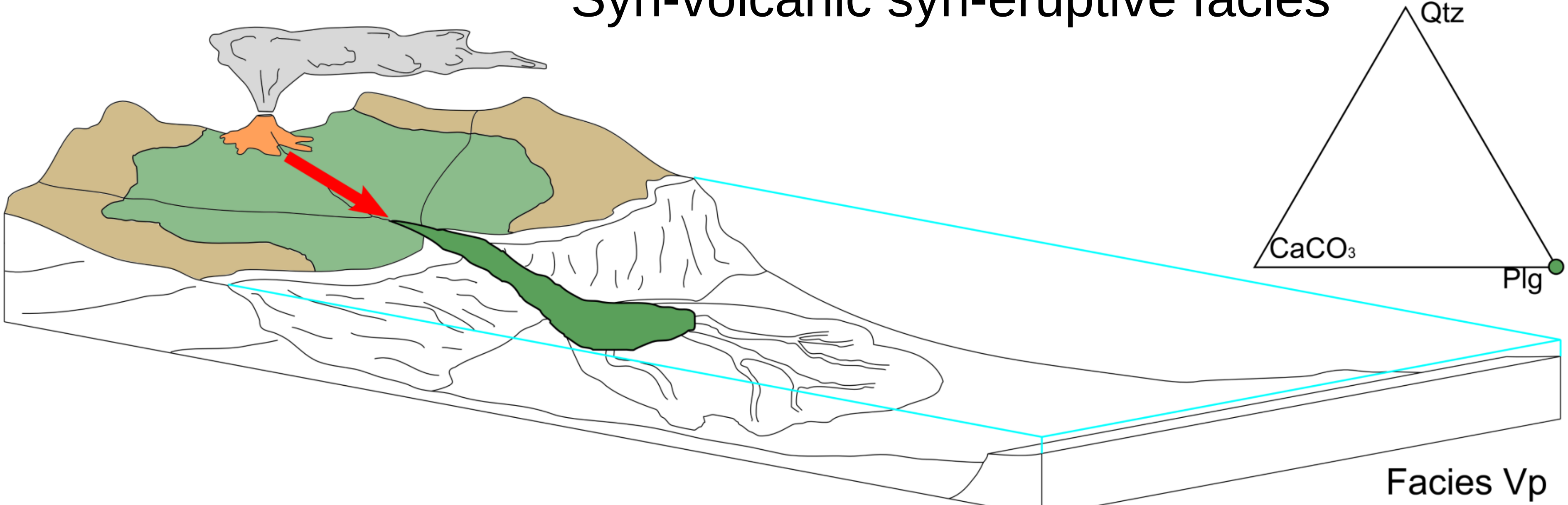


From Smith (1991)

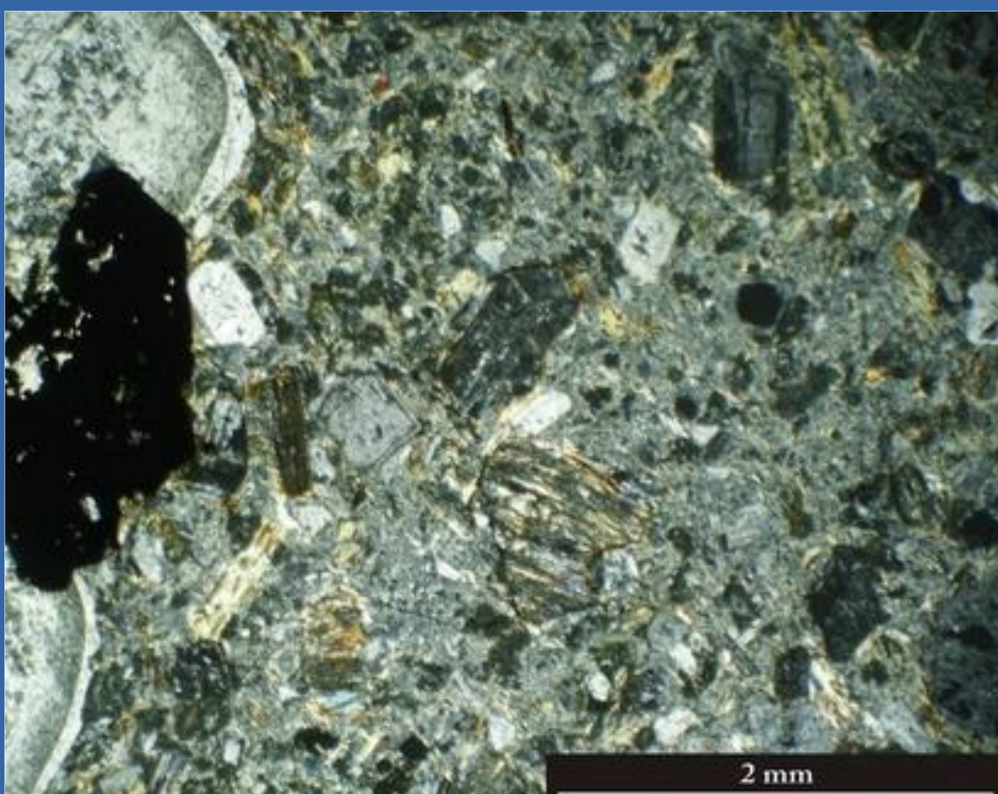


From Manville et al. (2005)

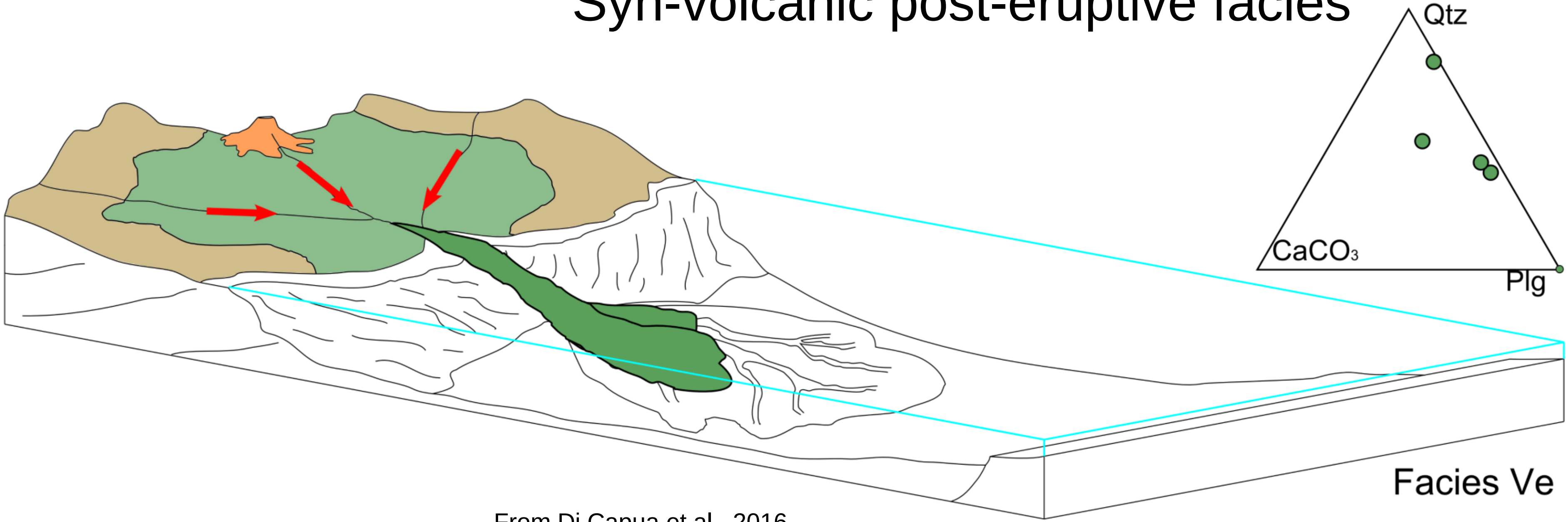
Syn-volcanic syn-eruptive facies



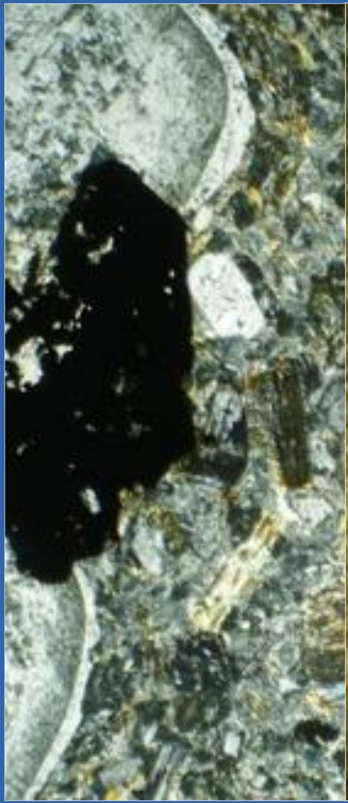
From Di Capua et al., 2016

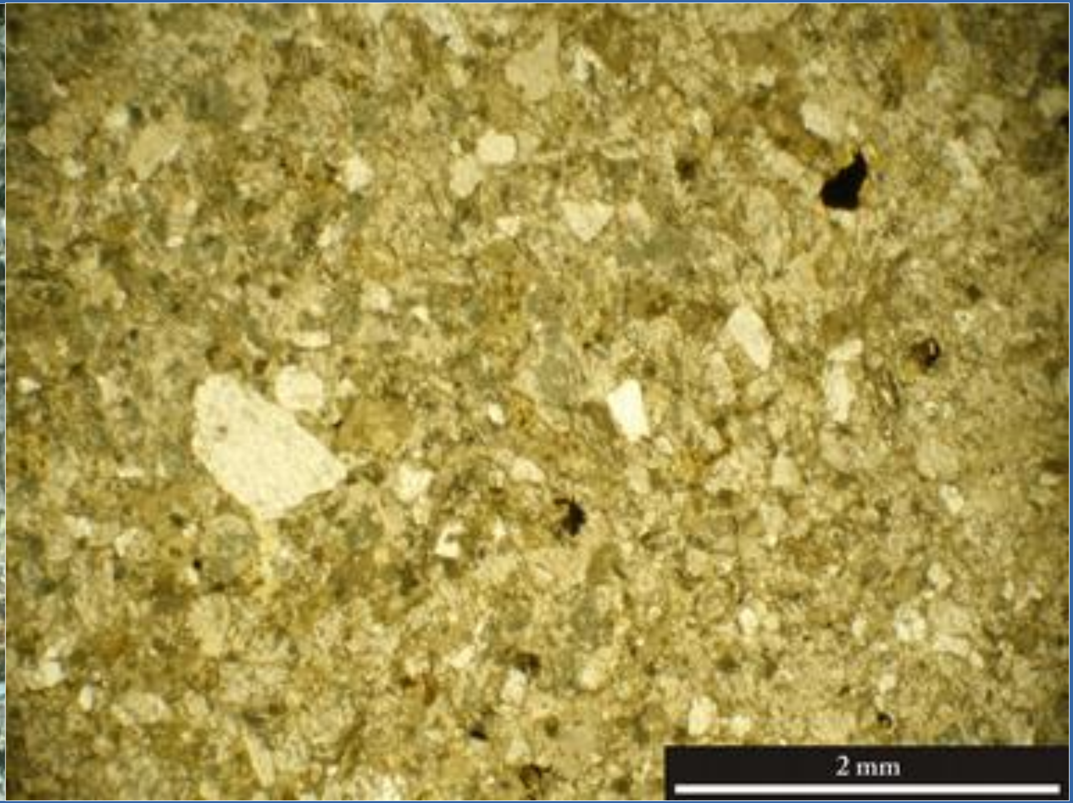


Syn-volcanic post-eruptive facies

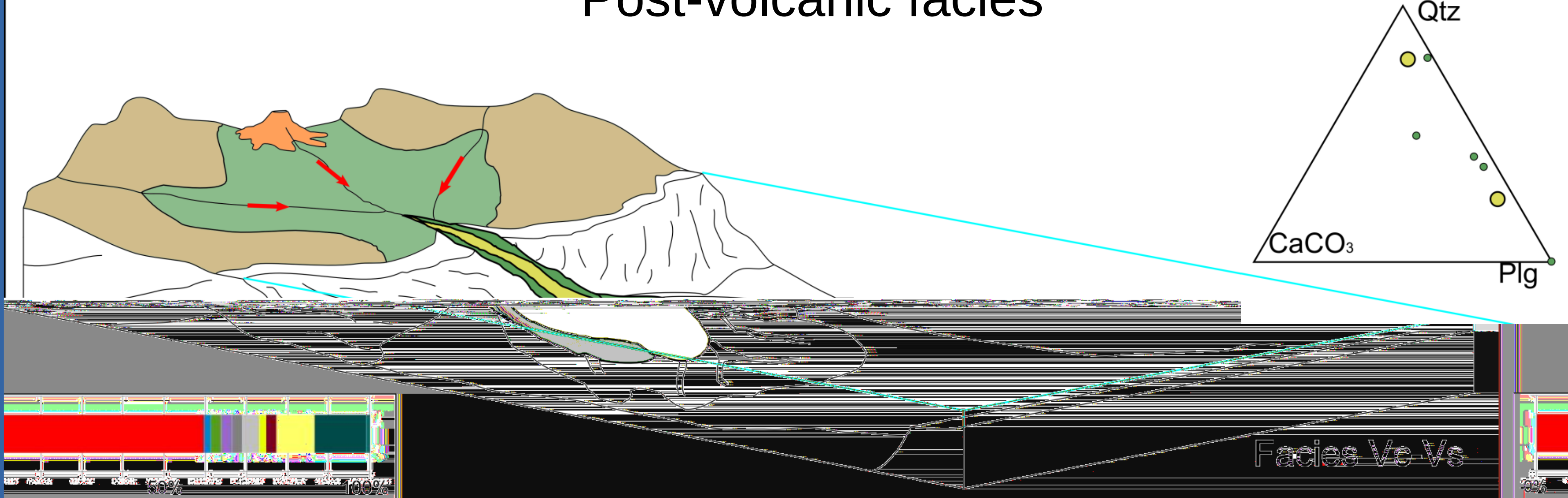


From Di Capua et al., 2016

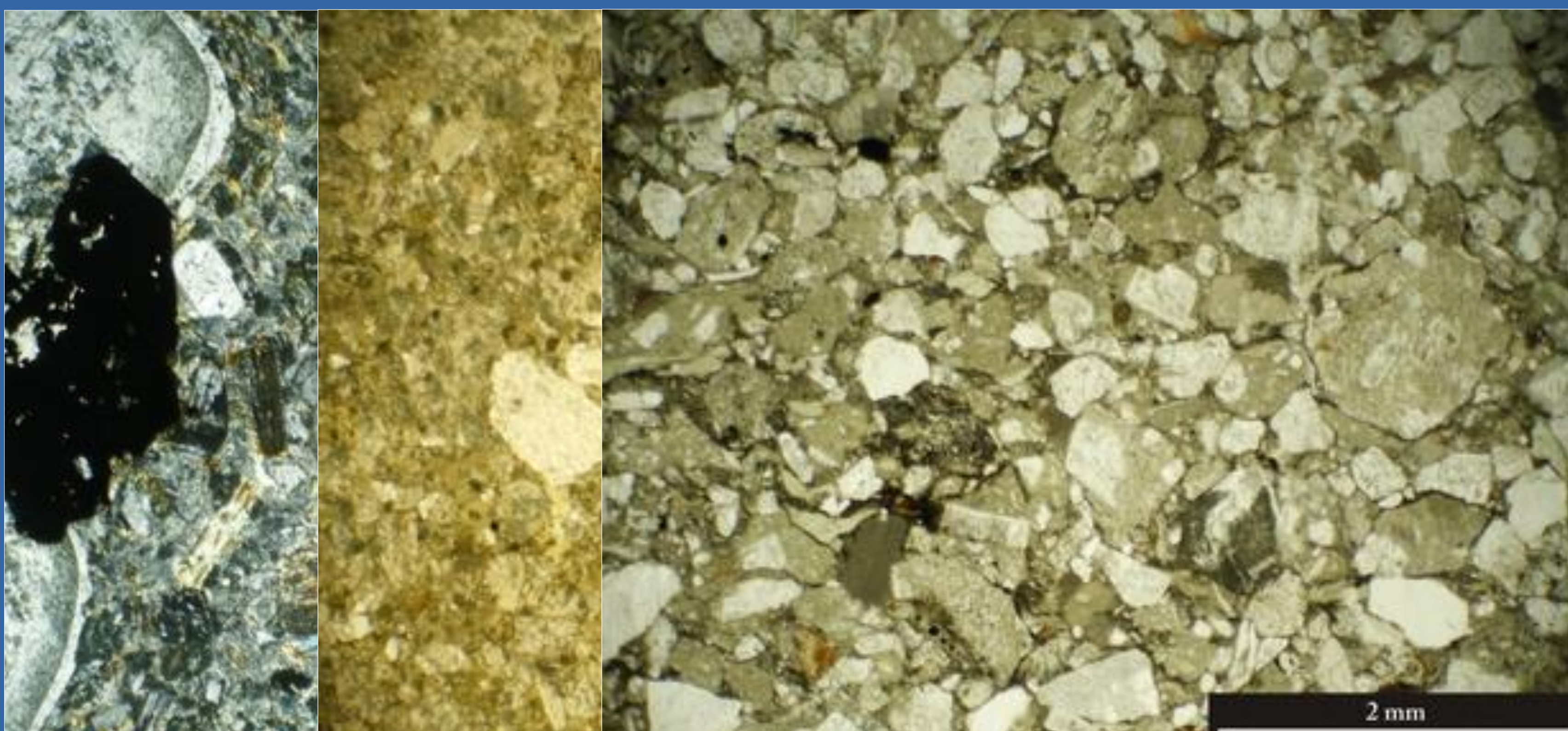




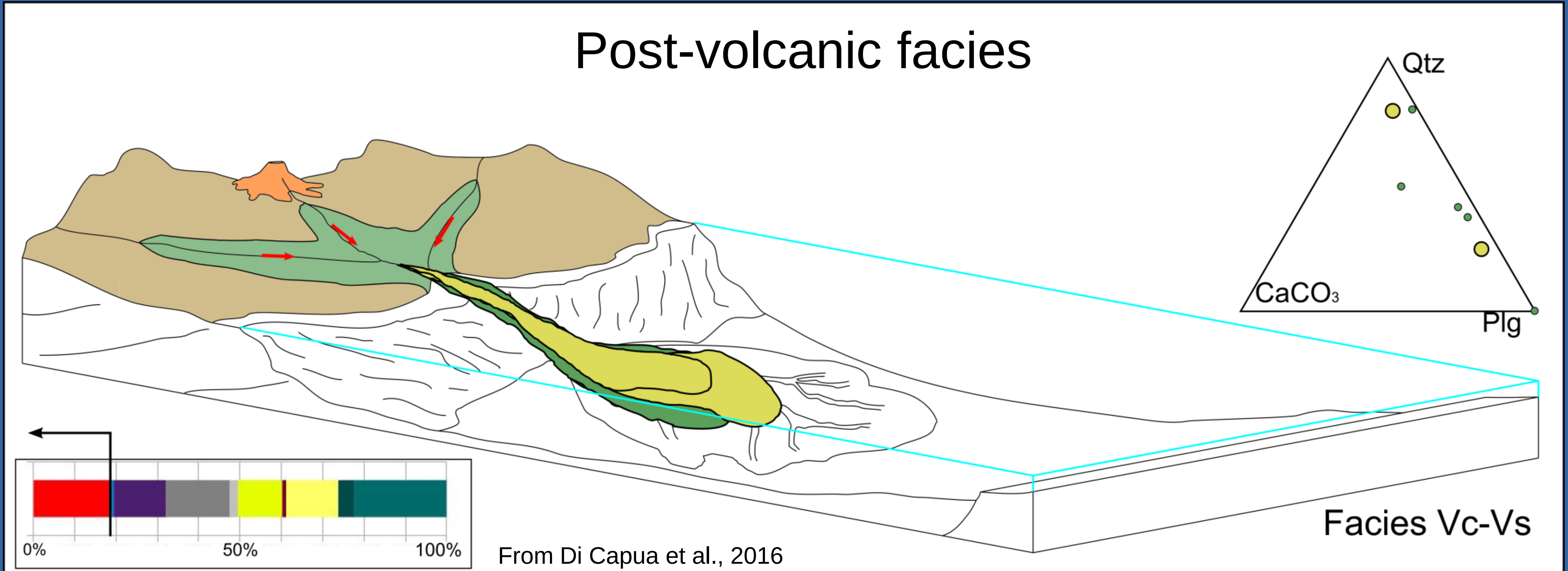
Post-volcanic facies



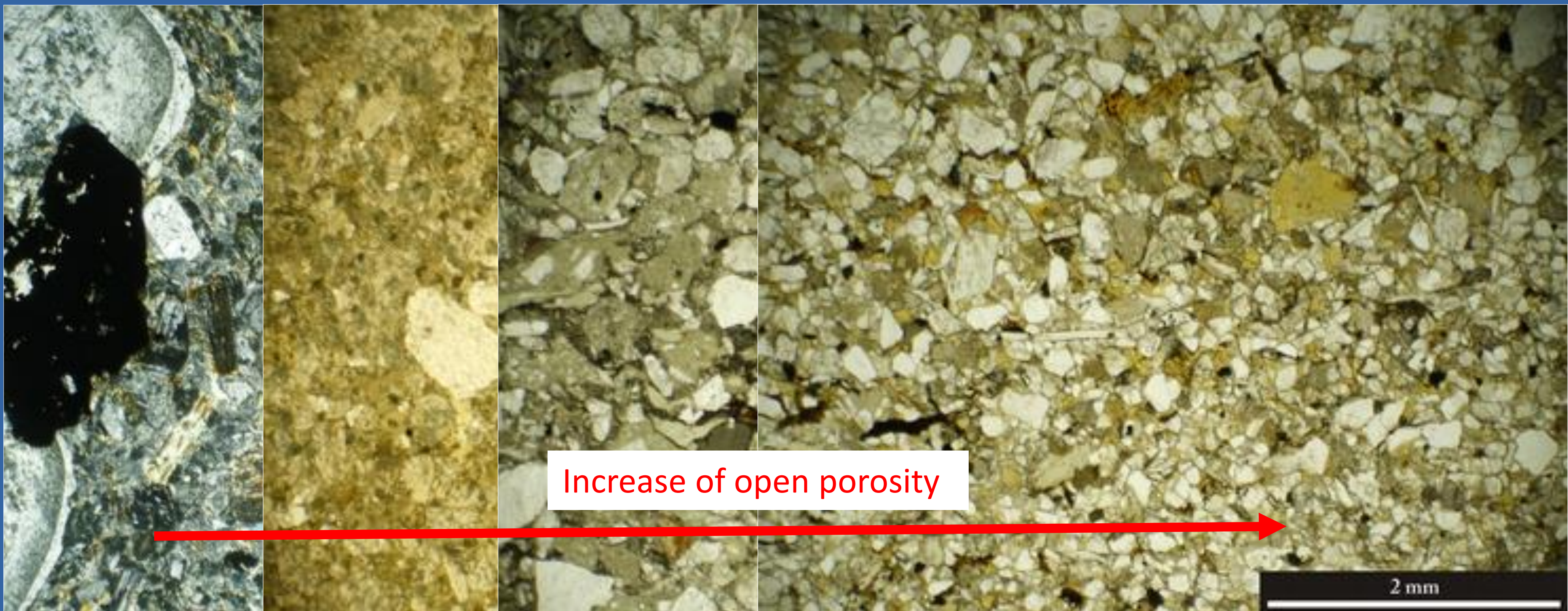
From Di Capua et al., 2016



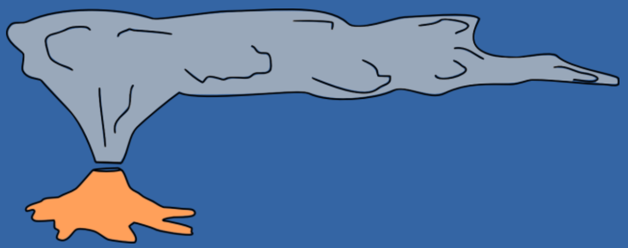
Post-volcanic facies

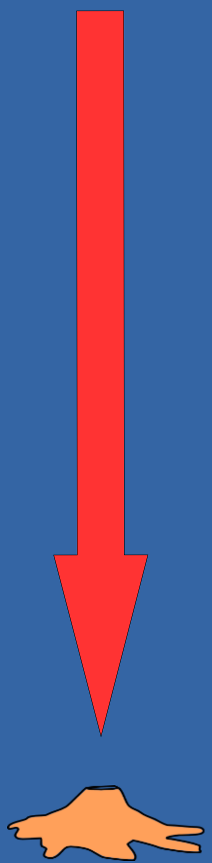


From Di Capua et al., 2016



Take-away points





The presented work and classification show the importance of a multidisciplinary and multiscale approach in the identification of the temporal relationship between volcanism and sedimentation, considered the main factor controlling the physical, minero-chemical, diagenetic and petrophysical properties of volcaniclastic sequences.

Thank you for your attention

Ongoing projects:

- Characterization of the microstructures of volcaniclastic deposits (petrography and SEM)
- Injection of water in PDCs: numerical modeling
- Volcaniclastic sedimentation in extensional basins: facies and geometries