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Review

Deep-Water Accumulation of Volcaniclastic Detritus from a Petrographic Point of View: Beginning a Discussion from the Alpine Peripheral Basins

Andrea Di Capua [1,*], Federica Barilaro [2] and Gianluca Groppelli [1]

[1] Institute of Environmental Geology and Geoengineering, Italian National Research Council (CNR), Via Mario Bianco 9, 20131 Milano, Italy; gianluca.groppelli@cnr.it
[2] Freelance Researcher, Via Agrigento SNC, 89900 Vibo Valentia, Italy; federicabarilaro@libero.it
* Correspondence: andrea.dicapua@igag.cnr.it

Abstract: The interpretation of eruptive mechanisms accumulating ancient submarine volcaniclastic sequences is still extremely challenging, particularly when no spatial nor temporal constraints are identifiable. The present work reviews petrographic results gained during the last few decades on three different Paleogene Formations accumulated around the Alpine and Apennine Mountain belts, discussing how their detritus could have been formed and moved from the volcanic centers to the depo-centers, taking into account the volcanic mechanisms which are at the base of the production, transportation and accumulation of volcaniclastic detritus. In doing this, we reconsider the classical diagrams of Folk and Gazzi–Dickinson, rediscussing their significance on the basis of how orogenic volcanism delivers detritus to the environment. In addition, this work highlights the need of the scientific community for gaining new petrographic data on modern sedimentary systems to better constrain interpretative criteria for the petrographic study of ancient volcano–sedimentary sequences.

Keywords: Oligocene; volcaniclastic; Taveyanne Sandstones; Cibrone Formation; Val d'Aveto Formation

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1. Introduction

Understanding the temporal relationships which exists between volcanism and the accumulation of volcaniclastic sequences in deep-water basins still represents an intriguing problem that often weaken our capability in the reconstruction of mechanisms governing source-to-sink systems (e.g., [1–3]). Differently from all the other siliciclastic detritus, volcaniclastic detritus can, in fact, either be produced by erosion or during volcanic activity through magma fragmentation and brecciation by different volcanic processes (e.g., [4,5]). In the same way, such detritus can be delivered to the sedimentary system either by sedimentary agents (by air, water, or both) or by volcanic processes (e.g., pyroclastic density currents (PDCs)) [6–8], and can be frequently mixed with non-volcanic detritus during its generation, transportation, or during both (e.g., [9,10]). This highlights how temporal relationships between volcanism and sedimentation can be extremely vague when recovered from ancient volcaniclastic sequences, and how their correct interpretation can make all the difference in the reconstruction of any sedimentary record [2,3].

Although the recognition of syn-sedimentary volcanic signals is becoming systematic (e.g., [11–13]), the scientific community still finds difficulties when approaching the identification of volcanic mechanisms beside the accumulation of volcaniclastic sequences. Most interpretations, in fact, simply considered them as produced by erosion and by the remobilization of piles of lavas or pyroclastic deposits (e.g., [14] and the references therein). The turning point arrived in 2006, when [15] described, for the first time, volcaniclastic sediments recovered from a submarine PDC accumulated in 2002 in front of the Montserrat Island (Central America). That work and the subsequent work of [16] stated how the transformation of PDCs entering seawater could completely transform their putative primary textural characteristics, accumulating thick volcaniclastic deposits as cold, water-supported mass-flow deposits. These works opened a new season in the interpretation of ancient volcaniclastic deposits, as shown, for example, by [17] for the Taveyanne Sandstones, an Oligocene formation accumulated in the Northern Alpine Foreland basin across France and Switzerland.

This work reviews the Taveyanne Sandstones and two other examples of volcaniclastic sequences (Cibrone and Val d'Aveto Formations) belonging to the Paleogene Alpine peripheral basins (Italy, France, and Switzerland, Figure 1), discussing how classical sandstones' classifications could be read under a new light. The paper wishes to be a first, constructive discussion on the need to develop new conceptual schemes, which are able to describe the volcanic as well as erosive processes controlling the production and transportation of volcaniclastic detritus across source-to-sink systems.

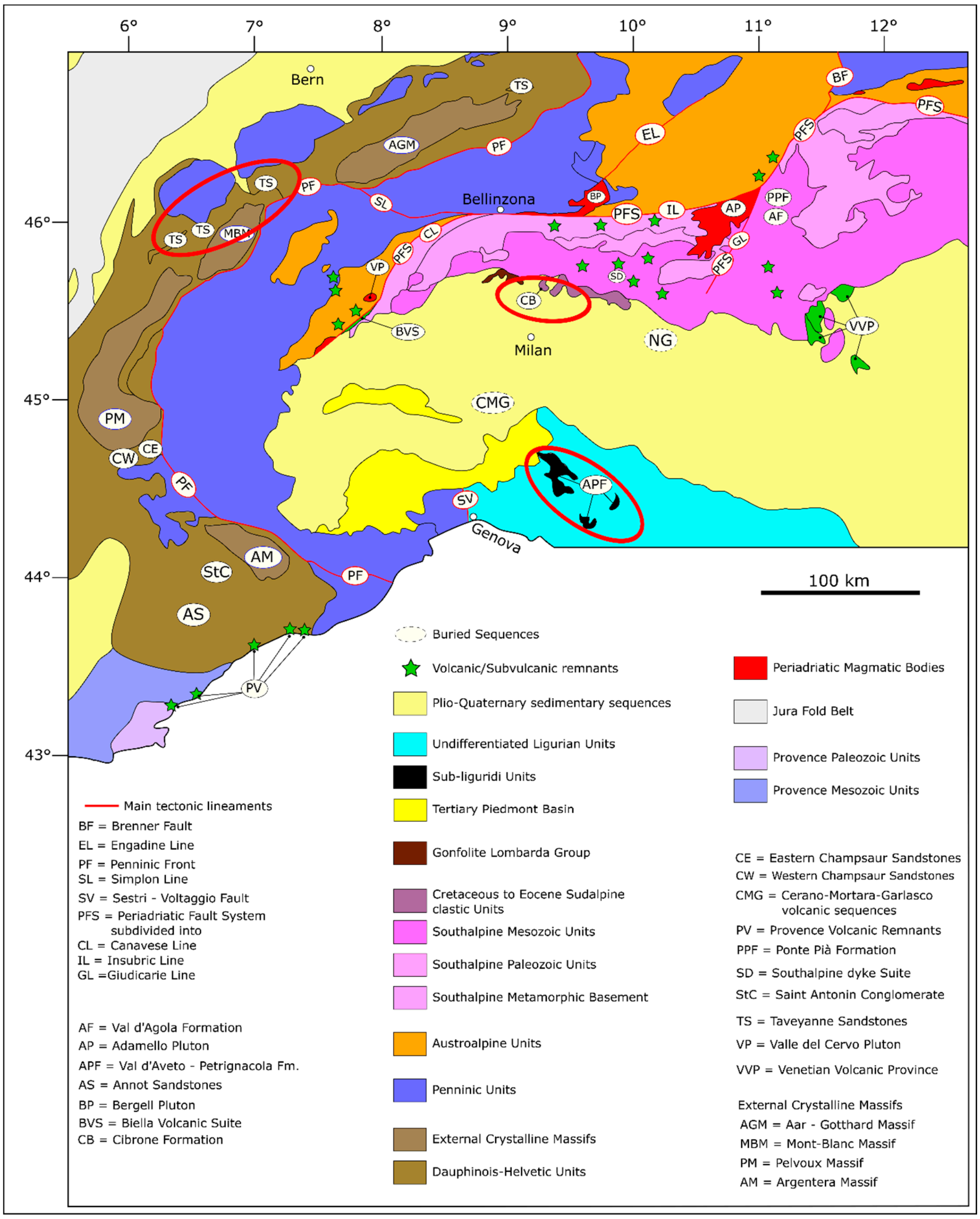

Figure 1. Regional Geological Maps of the Alps and Northern Apennines modified from [18]. The Formations object of this review are circled by red ovals.

2. Volcaniclastic Sequences within the Alpine Peripheral Basins

During the Paleogene, large amounts of volcaniclastic detritus were delivered to the Alpine peripheral basins, as recently reviewed by [18] (Figure 2). However, the paucity of preserved volcanic sequences and edifices, together with the accretion of the same Alpine and Apennines' belts, makes impossible the reconstruction of any Paleogene source-to-sink systems or the correct interpretation of such volcaniclastic layers. Among all the volcaniclastic sequences recovered and documented through the decades, this work takes into account one formation accumulated in the Northern Alpine Foreland basin (Taveyanne Sandstones, from SE France to SE Switzerland), another accumulated in the Adriatic Foredeep (Cibrone Formation, Northern Italy), and the last one accumulated in the Northern Apennines Foredeep (Val d'Aveto Formation, Northern Italy).

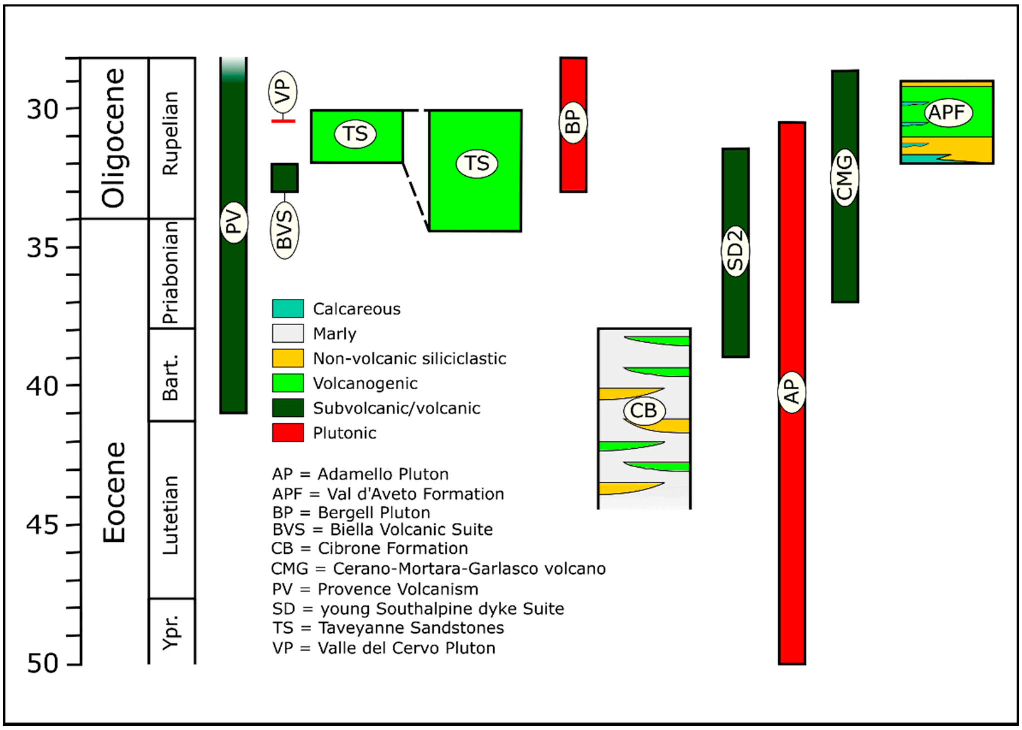

Figure 2. Magmatic manifestations and general stratigraphy of the sedimentary sequences included in the Northern Alpine Foreland Basin, Adriatic Foredeep and Northern Apennine Foredeep modified from [18] and ref. therein, limited to the Formations' object of this review.

2.1. Taveyanne Sandstones

Taveyanne Sandstones crop out between SE France and SE Switzerland and include a thick pile of submarine flow deposits, variably interbedded by muddy hemipelagic layers [17]. Biostratigraphically, their accumulation occurred from ca. 34 Ma to 29 Ma in SE Switzerland, and from ca. 32 Ma to 29 Ma in SE France. The volcaniclastic detritus has been dated between 41 and 29 Ma [19–22]. Petrographic analyses carried out by [17,20] document that volcaniclastic detritus is variably mixed with non-volcanic detritus liberated from the basement and the sedimentary covers of the Alps. This mixed signal agrees with the zircon thermochronology of [21,22]. Although the classical interpretation of such sequences defines them as the production of the rapid erosion of volcanic terranes (e.g., [14]), ref. [17] proposed a direct control of active volcanoes on the accumulation of the Formation, interpreting the pure volcaniclastic layers as putative PDCs disaggregated as they enter the water.

2.2. Cibrone Formation

The Cibrone Formation includes thin volcaniclastic turbidite layers, formally named plagioclase-arenites by [23,24]. The only geochronological constraint of the volcanic activity is provided by [25] (30.2 ± 2.7 Ma on apatite fission tracks), in contrast with the biostratigraphic ages of [26] (Upper Eocene). Beyond the geochronological discussion, which is useless for the aim of this article, a clear, direct relationship between volcanism and sedimentation is hypothesized by [23].

2.3. Val d'Aveto Formation

The Val d'Aveto Formation is a complex turbidite system, which is accreted in the Northern Apennine belt [27]. It consists of submarine mass-flow deposits with different origins, from calcareous to siliciclastic, among which [28,29] describe thick channelized deposits of PDCs and debris avalanches (DAs). Beyond them, volcaniclastic inputs are extremely important within the second half of the Formation, giving rise to beds up to 10 m in thickness [27,28,30]. The direct relationship between volcanism and sedimentation is also sustained by the geochronological data of [30–32], who indicate for the volcaniclastic detritus ages from ca. 31 to 29.2 Ma, which is coeval with the age of the Formation.

3. Gazzi–Dickinson versus Folk Methodology

3.1. Point-Counting Methodologies

Before any speculative discussions on how volcaniclastic sandstone compositions vary in relation to volcanic processes, attention must be paid to how methodologies can influence the recovery of information from samples. As reviewed by [33], different approaches and methodologies exist to determine the detrital modes of sands and sandstones, but this work will consider only the Gazzi–Dickinson and the Folk methodologies [34–37], as they are the most used.

The Gazzi–Dickinson method is the most used and appreciated point-counting methodology (e.g., [35–37]). It assigns sand-sized minerals and grains within larger fragments to categories of minerals and grains as they were loose. This allows the maximization of collecting data from any kind of samples, even though they are unsorted, with low effort and expense of time [37]. Particles counted "as they are" are defined as lithics. The solidity of such kind of methodology derives from the fact that huge amounts of data are available in the literature, both on ancient and modern depositional systems, ensuring total comparability among results in agreement with the "actualism law" (e.g., [38]).

Comparatively, the Folk method outlined in [34] does not count sand particles within larger fragments (defined rock fragments) separately, resulting in greater dependence on the grain size variations of the investigated samples.

Nevertheless, there are no compositional data on primary volcaniclastic deposits (sensu [4]) recovered through the Gazzi–Dickinson method. The only compositional data are those of [16] on submarine PDC deposits, gained in a similar method to that proposed by [34], thus classifying particles only for their nature (e.g., rock fragments and minerals), without separating sand-sized minerals from their larger fragments. For this, the first attempts in interpreting volcaniclastic layers under an actualistic point of view have been accomplished through the usage of the Folk point-counting methodology [8,17,28].

3.2. Ternary Diagrams

Ternary diagrams are offshoots of the above-mentioned methodologies. The uses of relative quantities of quartz, feldspars, and rock fragments to create a ternary diagram with seven categories is outlined in [34]. Such categories give descriptive names to sandstones and provide direct feedback on their composition but give no information on sourcing terranes and geodynamic settings. The author of [36] uses relative quantities of quartz, feldspars, and lithics in a diagram that identifies seven categories that are more informative about the terranes and geodynamic settings which sourced the sandy detritus (e.g., [39]). A third ternary diagram, proposed by [40] and improved by [41], just uses the particle classes of [36], but identifies fifteen categories with a descriptive significance.

4. Application

Through the years, different authors analyzed the volcaniclastic detritus within the aforementioned Formations, using the methodologies described in paragraph 3 [2,14,17,42]. In Figure 3, their results are plotted in the proper ternary diagram for an easier comparison. In addition, results gained through the Gazzi–Dickinson methodology have been also plotted in the ternary diagram [41].

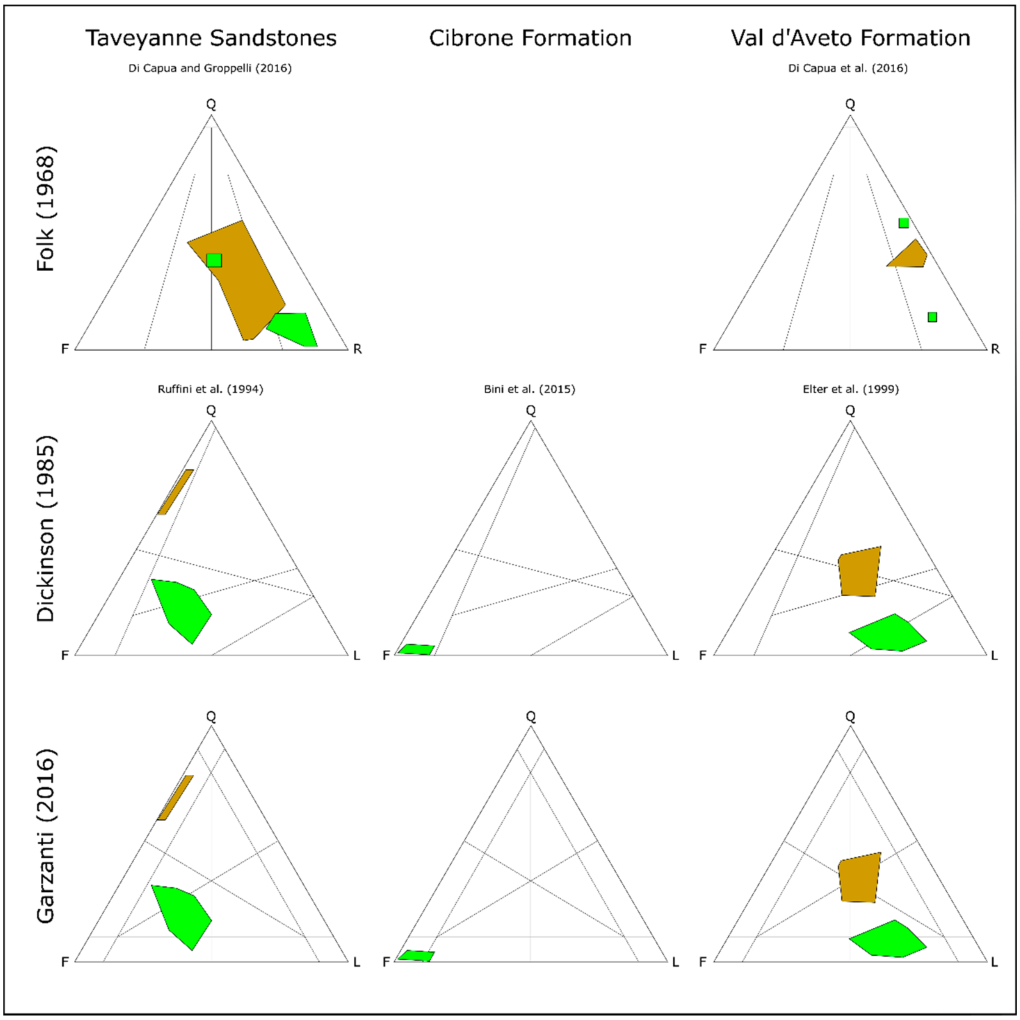

Figure 3. Ternary diagrams according to of the Formations considered in this work. Green fields group volcanogenic samples, brown fields group non-volcanic samples. Q = Quartz; F = Feldspars; L = Lithics; R = Rock Fragments.

4.1. Taveyanne Sandstones

On the basis of their petrographic composition, ref. [17] recognize two different groups of layers within the Taveyanne Sandstones.

The first group (Figure 4A) includes layers unsorted and highly enriched in volcanic components (from 65 to 92% according to [20]), whereas other components (sedimentary and metamorphic lithics, singles minerals of quartz, feldspar, muscovite and intrabasinal bioclasts) are minorly present [17,20]. Volcanic lithics are mostly intermediate in composition (two pyroxene-andesites and amphibole-andesite), with subordinate basalts, basaltic andesites, biotite-quartz dacites, and rhyolites [20]. Most of these fragments are very angular in shape, and some of them also show plastic deformation. This deformation affects fragments boundaries, fragments textures, and any mineralogical alignments within the fragments themselves [17]. Interstitial material includes fragmented plagioclase crystals. A fine-grained banded devitrified matrix, wrapping around the grains, is also documented in some samples [17].

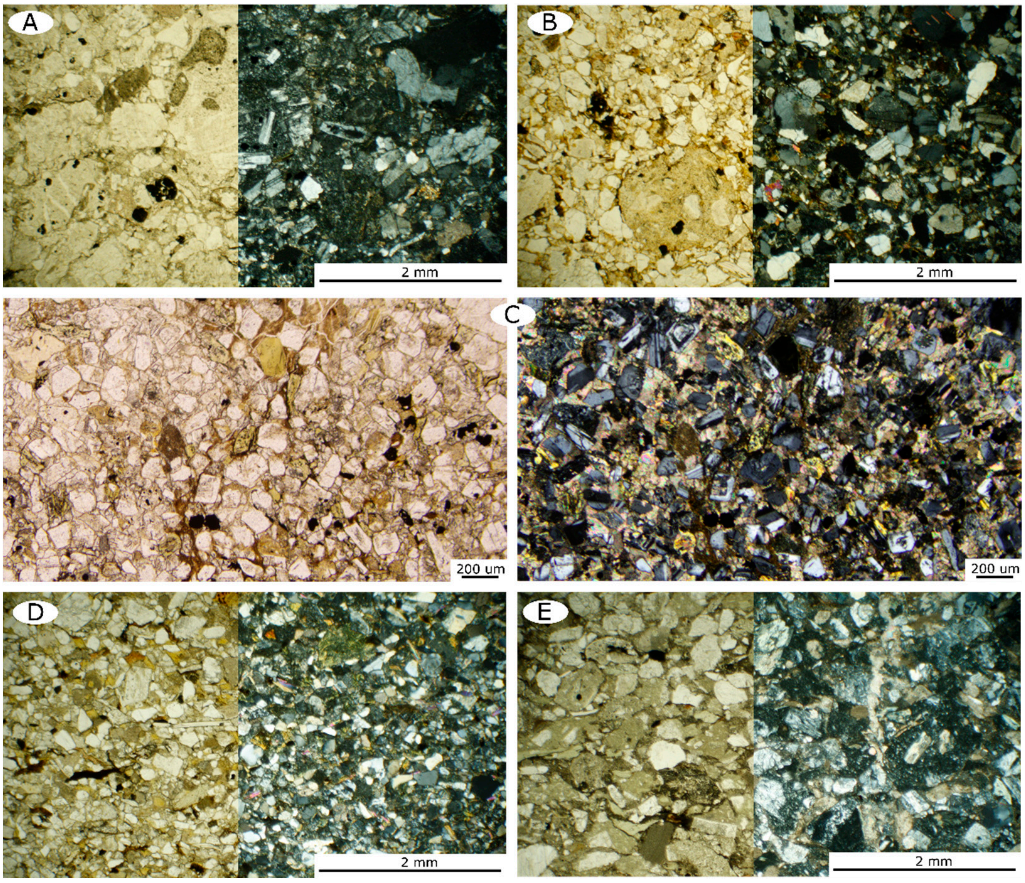

Figure 4. Thin section photographs of the reviewed Formations. (**A**): volcaniclastic layer within the Taveyanne Sandstones. (**B**): Polylithological layers from the Taveyanne Sandstones. (**C**): plagioclase-arenite layer from the Cibrone Formation. (**D**): polylithological layer from the Val d'Aveto Formation with volcanic rock fragments. (**E**): volcaniclastic layers from the Val d'Aveto Formation. Parallel nichols on the left side and crossed nichols on the right side of (**A**–**E**).

The second group (Figure 4B) includes medium to well-sorted layers, which are referred to as polylithological by [17]. They show, in fact, a more heterogeneous petrographic composition, with a net increase of non-volcanic components (e.g., metamorphic and sedimentary lithics, quartz and muscovite) with respect to volcanic ones [17,20]. In a couple of samples, volcanic lithics are even absent [20]. Grains are generally subangular to subrounded, and no fine-grained banded devitrified matrix wrapping around the grains has ever documented [17].

The point-counting results (Figure 3) of [17] (Folk method) and [20] (Gazzi–Dickinson method) show that sandstones are divided into two groups. According to the [34] method used by [17], the first group mainly includes litharenites, whereas the second group mainly includes feldspathic litharenites, and only one sample fall into the lithic arkose field. According to the Gazzi–Dickinson method, sandstones are quartzo-litho-feldspathic to litho-quartzo-feldspathic [41], and only two samples fall into the field of the feldspatho-quartzose sands. From a geodynamic point of view, these layers were sourced from a hypothetical transitional to dissected arc, with minor detritus from an uplifted basement (confer [36]).

4.2. Cibrone Formation

Petrography of the Cibrone Formation is well described by [23,24,42] (Figure 4C). Volcaniclastic layers are defined as "plagioclase-arenites" because of their enrichment in plagioclase single minerals, with subordinate amounts of amphibole, biotite, volcanic lithics, opaque minerals, zircon, and apatite.

Point-counting data (Figure 3) indicates that the volcanogenic layers of the Cibrone Formation are feldspathic sandstones [41]. According to [36], such kinds of sandstones are generally sourced by basement terranes in transform ruptures or uplifted as rift shoulders.

4.3. Val d'Aveto Formation

The Val d'Aveto Formation is characterized by three distinctive petrofacies, named A, B and C by [27,43]. Such categorization groups, when together, layer with terrigenous detritus (petrofacies A, Figure 4D), layers which are mainly volcaniclastic in composition (petrofacies B, Figure 4E), and non-volcanic layers, which are mainly composed of ultramafic detritus (petrofacies C). In Figure 3, petrofacies A and C are grouped together in the non-volcanic field. The stratigraphic distribution within the sedimentary sequence shows that petrofacies A mainly characterized the lower part of the Formation, whereas the central part is dominated by petrofacies B [27,28]. In this part of the sequence, primary volcaniclastic deposits have been documented by [28,29]. The upper part of the sequence is characterized by an alternation of layers of petrofacies A and B, overlaid on top by layers of petrofacies C.

In terms of composition, petrofacies A layers are composed of subrounded, low to medium metamorphic lithics, sedimentary lithics (sandstones, siltstones, cherts, dolostones, limestones, and intrabasinal grains), rare and rarely metamorphosed volcanic lithics (andesite, dacite, and rhyolite) quartz, feldspars, and accessory minerals (phyllosilicates and opaques) [27,28]. In terms of classification, these layers fall into the quartzo-litho-feldspathic, feldspatho-quartzo-lithic, quartzo-felspatho-lithic, and litho-quartzo-feldspathic fields of [41], whereas they are lithoarenites (and minorly feldspathic lithoarenites) according to [34]. According to [36], detritus has a mixed signature sourced by recycled orogenic terranes and transitional to dissected arc terranes.

Layers of petrofacies B are dominated by angular volcanic lithics (up to 65% of the detritus) and subrounded terrigenous grains alike those of petrofacies A [27,28]. Petrofacies B falls into the feldspatho-lithic and quartzo-feldspatho-lithic fields of [41], whereas they are lithoarenites according to [34]. According to [36], detritus has an undissected to transitional magmatic arc signature.

Petrographic C has large amounts of ultramafic grains that dominate over metamorphic and sedimentary lithics, quartz, and felspars [43], falling into the feldspatho-quartzo-lithic and quartzo-felspatho-lithic fields of [41]. They were not classified according to [34]. According to [36], detritus has a mixed signature sourced by recycled orogenic terranes and transitional to dissected arc terranes. In Figure 4, petrographic A and C are grouped together, holding a similar geodynamic significance in this work.

5. Discussion

Section 4 describes the three different volcaniclastic systems from a petrographic point of view. Combining such results with field observations and geochronological data, it is possible to make some considerations about the usage of classical petrographic methodologies and the information they give on the relations between volcanism and sedimentation.

5.1. Massive Erosion of Volcanic Terranes versus Explosive Volcanic Activity

Under the word erosion, there are many processes that liberate detritus to the environments (e.g., debris-flows, rock avalanches, and fluvial erosion). All of these processes could locally influence drainage patterns and bring a rapid supply of particles to sedimentary systems, but their incidence in the petrographic record is generally minimal as they are local phenomena impacting large source areas. On the contrary, volcanic edifices present vents from which particles are liberated and widely dispersed in the surrounding environments. Explosive volcanic eruptions can bring about this, and each explosive activity retains a typical signature. Consequently, was the Paleogene detritus only provided by the passive erosion of volcanic piles, or was it caused by the Periadriatic volcanism that favored the accumulation of such kinds of sequences?

The geodynamic setting of the Alps in the Paleogene, together with the volcanic lithic types within the aforementioned basins, could help to provide a comprehensive answer to the problem. A continental volcanic arc generally groups together stratovolcanoes with an average life of 1 Ma (e.g., [44]), characterized by periods of construction and periods of destruction [45]. In such kinds of volcanoes, intermediate to acid magmas are poorly mobile and consequently favor the extrusion of lava domes and, minorly, thick blocky lava flows (e.g., [46]). Domes are unstable structures that frequently collapse (e.g., [47]), generating PDCs that transfer large amounts of block-sized and ash-sized (the latter granulometrically corresponding to sand and mud) particles tens of kilometers away from the eruptive centers, toward the surrounding environments (e.g., [48]).

Although PDCs are generally gas-supported hot flows, the most common PDCs generated by dome collapses, named block and ash flows (BAFs), tend to resemble cold mass-wasting deposits rather than classical ignimbrites because they rarely undergo welding processes, owing to the very scarce presence of pumice and glassy materials [49], and the relative low temperature. The welding process can be further inhibited when subaerially generated BAFs move underwater, where the mix between cold water and hot flowing particles transforms BAFs into cold, water-supported turbidite submarine flows [8,15,16]. It follows that most BAF deposits accumulated below the water might easily be mixed up with non-volcanic deposits, and the either the presence or absence of pumices, shards, or both, cannot be considered the only criterion to distinguish between primary volcaniclastic deposits (sensu [4]) and reworked or epiclastic deposits. In addition, hydrological and morphological variations, imposed by the accumulation of PDCs in any drainage patterns, drastically increase the sediment yield of rivers that rework large amounts of loose detritus for tens to hundreds of years after the eruptive events (e.g., [7]).

Under a geological timescale, the generation and transportation of volcaniclastic detritus is a single, instantaneous supply that leads to the accumulation of different layers. In these layers, the enrichment in volcaniclastic particles decreases, turning away from the eruptive event (e.g., [2]), and is then diluted by the non-volcanic particles of the terrains surrounding the eruptive center. In all the described examples, these pulsing enrichments are recognizable within the ternary diagrams.

On the contrary, the production of volcaniclastic sediments via weathering/or erosion would imply an almost constant supply of volcaniclastic particles to the sedimentary routine system, controlled primarily by the proneness of any volcanic rocks to be disaggregated into transportable particles. Such proneness is normally very much less than that of most of the lithologies surrounding volcanoes in orogeny, such as clastic sedimentary sequences and many para-derived metamorphic terranes (e.g., [8]). This results in the rapid dilution of the volcaniclastic signal by any non-volcanic signals, providing detritus to the sedimentary routine system, and creating the impossibility to accumulate thick volcaniclastic sequences solely as products (e.g., [2,28]).

Therefore, the abrupt accumulation of thick volcaniclastic sequences within orogenic peripheral basins might generally be driven by syn-sedimentary volcanic activity [2], rather than the tectonically and climatically driven focused erosion of penecontemporaneous volcaniclastic piles (e.g., [14,50]).

5.2. Variation of Lithic Geochemistry and Textures: Single versus Multiple Sources

Chemical compositions and textures of volcanic fragments are two other parameters that must be handled carefully. Differences in the geochemistry of lithics are a function of regional or local scale variations, or a combination thereof. Volcanic processes play a fundamental role on both scales, but the latter is poorly considered in sedimentary petrography.

Magmas, in fact, evolve on long- and short-timescales in a sort of matryoshka process; long-timescale evolutions often include short-timescale local evolutions (e.g., [51,52]). Dome features are primarily controlled by these latter variations, which induce rapid changes in their geochemistry (e.g., [52]), and are consequently recognizable in the sediments they produce through BAFs and erosive processes [53]. In the same way, lava domes are also subject to the internal stresses caused by a rise in magma during the growth phases [54,55]. Such kinds of stresses induce the generation of internal textural variations [46,55,56] that can potentially control the sediment composition and texture of deriving PDCs [16].

It follows that, in a volcaniclastic turbidite system fed by a single lava dome, volcaniclastic particles can be characterized by geochemical trends and textural variations that do not hold any regional variations but could derive from the internal organization and geochemical evolution of a single sourcing dome (e.g., [16,57]).

5.3. Crystal Enrichments: Is Maturation Necessary?

Another important point that deserves consideration is the variation of lithic/mineral ratios within the sedimentary layers. Volcaniclastic detritus represents the best example of sediments that do not linearly undergo the "maturation" principle, strengthening what [58] wrote. Mineral enrichments are, in fact, firstly determined by the generating of the volcanic processes of fragmentation [8,48,59], by the interaction between hot PDCs and cold water during their motion from subaerial to subaqueous environments (e.g., [60]), or by a combination thereof. Crystals suspended into finer groundmass could move tens to hundreds of kilometers away before settling, and eventually being modified by water or air. When the hosting PDCs become welded, their supply to the environment is slow and limited, whereas when PDCs are loose (in most cases), crystals can rapidly be delivered into sedimentary systems (e.g., [61]).

It follows that any of the fields within the ternary diagrams could potentially contain primary volcaniclastic deposits. Rapid vertical changes in detritus composition, from volcaniclastic sensu lato to non-volcaniclastic, could be a signal of the involvement of active volcanoes in the supply of volcaniclastic detritus.

6. Final Remarks

Provenance analyses deserve a constant, increasing interest in the identification of the temporal relationship which exists between the production and accumulation of volcaniclastic sediments, especially when combined with geochronological techniques (e.g., [62,63]). Nevertheless, there are still lots of uncertainties in retrieving specific volcanic processes from volcaniclastic sequences, limiting a deep comprehension on how environments and volcanoes interact together during and after the main eruptive events.

For this, the present work represents the first discussion on how to link specific features within volcaniclastic sequences to eruptive activity and mechanisms, to volcanic center behaviors through a classical provenance approach, or to both, reviewing literature data of three Alpine and Apennine Paleogene Formations (Taveyanne Sandstones, Val d'Aveto Formation, and Cibrone Formation). Although limited to a single volcanic process (BAFs) and geodynamic setting (collisional volcanism), this review highlights the key-points which should be taken into account when interpreting volcaniclastic sequences such as those described here. Independent from the methodological approach used during the provenance analyses, the complexities of the magmatic systems are, in fact, hard to detect, if they are only based on the petrographic analyses on volcaniclastic detritus. The most important gap in using this approach is the paucity of data collected on modern environments, which are needed to identify how volcaniclastic detritus is produced and appears once settled, as well as how the environmental processes (transport mechanisms, weathering, and erosion) rapidly obliterate primary features and impose barriers in our interpretation process.

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