

PERIODICO di MINERALOGIA
established in 1930

An International Journal of
MINERALOGY, CRYSTALLOGRAPHY, GEOCHEMISTRY,
ORE DEPOSITS, PETROLOGY, VOLCANOLOGY
and applied topics on Environment, Archaeometry and Cultural Heritage

Carbonate-rich pyroclastic rocks from central Apennines: carbonatites or carbonated rocks? A commentary

ANGELO PECCERILLO*

Dipartimento di Scienze della Terra, Università di Perugia, Piazza Università, 06100 Perugia, Italy

ABSTRACT. — The Pleistocene association of melilititic ultrapotassic kamafugites and carbonate-rich pyroclastic rocks from Apennine has been interpreted to represent a melilitite-carbonatite province, such as those typically found in intra-continental rift settings. Kamafugitic lavas have incompatible element and REE patterns that closely match those of leucite tephrites from the nearby Roman Province. Carbonate-rich pyroclasts have similar trace element patterns as kamafugites and Roman rocks, but, when single carbonate-rich pyroclastic rocks are compared with the associated kamafugitic lavas from the *same volcano*, they show a depletion for all the incompatible elements, which becomes stronger as the amount of carbonate fraction increases. This shows that the carbonate fraction is geochemically barren and its presence in the carbonate-rich rocks generates a dilution for almost all the elements. Oxygen isotope ratios of carbonates in these volcanic rocks are invariably high ($\delta^{18}\text{O}$ in the range +21 to +28). Phenocrysts from kamafugitic lavas also have high concentrations of heavy oxygen ($\delta^{18}\text{O} = +11$ to +14).

These data cast serious doubts on the hypothesis that the carbonate-rich pyroclastics from central Italy represent carbonatitic magmas. Geochemical and isotopic data strongly suggest that these rocks

represent fragmented kamafugitic magmas, which have suffered addition of geochemically barren carbonate material from wall rocks. Geological data make this hypothesis likely, inasmuch as the volcanoes from the internal Apennines are monogenetic centres, which cut through some thousand meters of carbonate rocks of the Apennine sedimentary sequences.

KEY WORDS: *ultrapotassic magmatism, carbonatites, intra-Appennine magmatism, Central Italy.*

RIASSUNTO. — La coesistenza di rocce piroclastiche ricche in carbonati e di lave melilitiche ultrapotassiche (kamafugiti) nell'Appennino centro-settentrionale è stata interpretata come un'associazione melilitico-carbonatitica, analoga a quelle di alcune rift continentali. Nei vulcani di San Venanzo e Capaello, le piroclastiti ricche in carbonati formano la base di una sequenza eruttiva che è chiusa da lave kamafugitiche. Le piroclastiti ricche in carbonati mostrano composizioni isotopiche di Sr-Nd-Pb e rapporti degli elementi incompatibili sostanzialmente identici a quelli delle lave. Tuttavia, l'abbondanza assoluta di quasi tutti gli elementi (inclusi gli elementi incompatibili) è più bassa nelle piroclastiti a carbonati che nelle lave ad esse associate nello stesso centro vulcanico. Inoltre, il grado di impoverimento degli elementi

* E-mail: pecceang@unipg.it

incompatibili aumenta con l'abbondanza della frazione carbonatica. A San Venanzo le rocce piroclastiche posseggono circa 10% di calcite e mostrano un abbassamento modesto delle concentrazioni degli elementi incompatibili rispetto alle lave dello stesso centro. A Cupaello, le piroclastiti sono costituite per circa la metà da calcite e presentano un impoverimento degli elementi incompatibili di circa il 50% rispetto alle lave sovrastanti. I rapporti isotopici dell'ossigeno dei carbonati mostrano valori elevati ($\delta^{18}\text{O}_{\text{SMOW}} = +21$ a $+28$), lontani dalle composizioni delle rocce magmatiche conosciute e prossimi a quelle dei sedimenti carbonatici. Alti valori di $\delta^{18}\text{O}_{\text{SMOW}}$ (da $+11$ a $+14$) sono stati rilevati anche nei fenocristalli della lave kamafugitiche.

I dati geochimici e isotopici sollevano seri dubbi sull'ipotesi che le rocce piroclastiche ricche in carbonati dell'Appennino centro-settentrionale rappresentino magmi carbonatitici. Infatti, le carbonatiti di sicura origine magmatica studiate a livello globale presentano elevate concentrazioni degli elementi incompatibili, che sono spesso molto superiori a quelle delle lave kamafugitiche. La forte diluizione degli elementi incompatibili nelle piroclastiti a carbonati rispetto alle lave dello stesso vulcano indica che la componente carbonatica è geochimicamente sterile, escludendo una sua origine magmatica. Il complesso dei dati è meglio e più semplicemente spiegato assumendo che i carbonati delle rocce piroclastiche sono legati a qualche tipo di interazione (es. dissoluzione e successivo smescolamento) tra i magmi kamafugitici e le rocce sedimentarie carbonatiche incassanti. Tale ipotesi è geologicamente plausibile in quanto i centri vulcanici intra-Appenninici sono costituiti da modeste quantità di magma messe in posto nel corso di una singola eruzione dopo aver attraversato migliaia di metri di sedimenti carbonatici.

PAROLE CHIAVE: *magmatismo ultrapotassico, carbonatiti, magmatismo Intra-Appenninico, Italia centrale.*

INTRODUCTION

The idea that the carbonate-rich rocks and associated melilite-bearing kamafugites from the central Apennines represent a carbonatite-melilititic association has gained wide acceptance, and yet the many objections to this interpretation that Peccerillo (1998) enunciated have not been answered. Whatever the reason

of this unconcern, I had decided against any further discussion of the topic. However, the Editor of this journal has repeatedly asked me to set down my case again and I have, reluctantly, agreed to do so.

In reiterating my earlier arguments I focus on the monogenetic volcanoes of San Venanzo, Cupaello and Polino, which are the most celebrated of the carbonate-rich volcanic rocks, and are the only places in Central Italy where carbonate-rich pyroclastic rocks are associated with silicate lavas in the same centre.

Carbonatite has been discussed since at least the 1920s (e.g. Bowen, 1926) but, while a magmatic origin has generally been accepted (see, however, Lentz, 1999), there are occurrences where ambiguity is present. Barker (1993) warned that if, on the one side, some magmatic carbonatites may be affected by strong subsolidus modification that obliterates primary textural and compositional magmatic characters, on the other side some non-magmatic carbonate-rich rocks may show textural and compositional characteristics that can lead to misidentifying them as carbonatites.

Keeping in mind these words of wisdom, in the following paragraphs I will try to scrutinize evidences supporting a carbonatitic nature as well as objections and doubts, leaving as little as possible to personal interpretation.

Francis Bacon worried that scientific observation might be prejudiced by previously formed theory, but I have attempted to avoid this trap by dealing only with the data on carbonate-rich rock, which have been published by the carbonatite proponents, avoiding, as much as possible, employing the data which I have collected myself. This was also my approach in 1998.

SUMMARY OF ROCK CHARACTERISTICS

Carbonate-rich rocks occur as pyroclasts in a number of small volcanoes from the central Apennines (Stoppa and Woolley, 1997), the best studied examples being San Venanzo, Cupaello and Polino (Fig. 1). In the first two

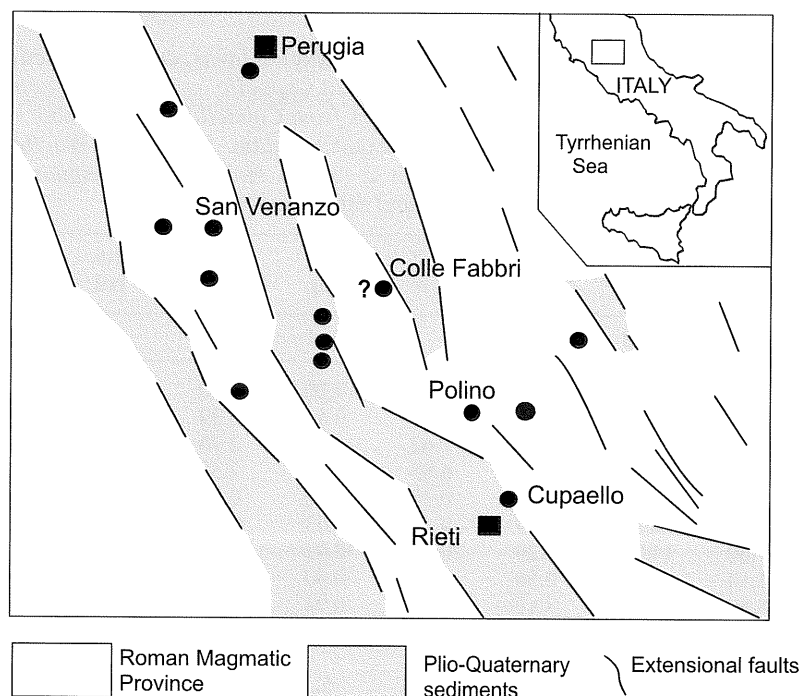


Fig. 1 – Schematic distribution of Recent volcanism (filled circles) in the internal zones of Apennines in central Italy. Modified after Castorina *et al.* (2000). Note: That the igneous origin of Colle Fabbri is dubious (Melluso *et al.*, 2003).

examples the pyroclastic rocks are overlain by lava flows and dykes. The volcanoes have ages between 0.6 and 0.2 Ma, are monogenetic, and have penetrated 2000-3000 m of sedimentary carbonate rocks (e.g. Stoppa and Woolley, 1997).

Lava flows and dykes are mafic (MgO ~ 10-12 wt.%) strongly SiO₂ undersaturated, and ultrapotassic. SiO₂, Al₂O₃ and Na₂O contents are low, whereas K₂O/Na₂O, and CaO are high (Table 1). The rocks are, therefore, ultrapotassic kamafugites (Sahama, 1974; Gallo *et al.*, 1984; Peccerillo *et al.*, 1988). The principal minerals of the lavas include melilite, olivine, clinopyroxene, monticellite and plogopite. The pyroclastic rocks range from melilitite to trachyphonolite (Stoppa and Lavecchia, 1992); in addition to the same minerals as the lavas, they contain sanidine, calcite, and a number of exotic minerals such as zirconian schorlomite, baddeleyite,

cuspidine, Th-rich pyrochlore, and perovskite. Both the kamafugitic lavas and the carbonate-rich pyroclastic rocks show incompatible element patterns and radiogenic isotope signatures which are similar to those of the volcanic rocks in the nearby Roman province (Figs. 2, 3).

CARBONATITES OR CARBONATED ROCKS?

The essential question is whether the carbonate-rich pyroclastic rocks of the central Apennines are magmatic carbonatites, or whether they are fragmented silicate rocks into which calcite has been incorporated during their passage through the sedimentary rocks which they have intruded. The principal arguments that have been advanced in favour of their being carbonatites are:

TABLE 1

Major, trace element and isotopic data for Italian kamafugitic lavas, and associated carbonate rich rocks. 1. Average San Venanzo lava; 2. Average of Cupaello lava; 3. Carbonate volcanic rocks from San Venanzo; 4. Carbonate volcanic rock from Cupaello; 5. Carbonate rocks from Polino; 6. Average leucite tephrite from Vulsini. Source of data: Stoppa and Woolley (1997); Conticelli and Peccerillo (1992); Conticelli et al. (2002), Holm and Munksgaard (1982) and Turi et al. (1986) and references therein.

	San Venanzo	Cupaello	pc9-1 sv	pc9-2 sv	c11a cup	C11b cup	Po2-5 pol	Po2-3 pol	Lc-tephrite
	1	2	3	3	4	4	5	5	6
SiO ₂	41.54	43.85	39.70	34.60	19.20	19.50	16.00	15.00	48.06
TiO ₂	0.69	1.15	0.56	0.67	0.43	0.39	0.51	0.44	0.72
Al ₂ O ₃	12.00	7.99	8.16	7.62	2.60	2.70	3.90	3.80	14.28
FeO _t *	6.49	7.75	5.50	6.85	2.60	2.38	4.96	3.98	7.17
MnO	0.11	0.12	0.10	0.13	0.06	0.05	0.07	0.06	0.14
MgO	12.77	10.56	7.39	9.42	8.03	7.88	7.31	5.34	8.07
CaO	15.60	14.91	18.20	20.10	32.02	31.90	38.30	39.40	13.30
Na ₂ O	1.14	0.40	0.56	0.62	0.80	0.01	0.05	0.09	1.26
K ₂ O	8.40	8.68	3.89	4.89	0.94	0.91	0.49	0.71	5.20
P ₂ O ₅	0.42	1.23	0.23	0.28	0.48	0.67	0.59	0.61	0.32
Mg#	81	75							71
Sc	21	18			5.3	5.2	10	8.7	32
Cr	800	60	528	721	33	27	490	392	320
Co	40	34	49	52	22	16	34	30	35
Ni	141	82	137	177	30	26	342	236	100
Rb	471	568	320	476	139	166	51	81	421
Sr	1773	3684	939	1276	1160	1178	1897	1424	949
Ba	667	4343	534	630	895	940	2216	902	791
Nb	15	46	12	13	20	21	16	14	14
Zr	317	835	237	291	286	279	337	263	212
Y	38	56	22	15	15	15	22	23	29
La	87	278	62.7		95		111	89	79
Ce	182	530	135		184		232	175	150
Nd	86	239	69		81.7		113	80	71
Sm	18.1	40.0	14.2		15.1		22.2	14.6	11.4
Eu	3.1	7.2	2.8		2.9		4.7	2.8	2.2
Gd			11.3		12.2		15.8		9.5
Tb	1.3	2.7	1.3		1.2		1.7	1.5	1.1
Yb	2.4	2.7	2.0		0.9		1.5	1.4	1.5
Lu	0.4	0.5	0.3		0.1		0.2	0.2	0.3
Cs	33.1	72.8			39.0	45.0	5.0	16.0	25.7
Hf	8.8	23.2			7.0	8	8.0	7.0	5.1
Ta	0.9	3.6			1.0	0.8	0.9	0.8	0.6
U			6.3		4.1	5.5	8.8	5.9	
Th	34	131	26	30	42	41	50	37	36
δ ¹⁸ O	+12	+12	+23		+21		+22.4	+22.7	+7
⁸⁷ Sr/ ⁸⁶ Sr	0.71039	0.71124	0.7106				0.7104		0.71015
¹⁴³ Nd/ ¹⁴⁴ Nd	0.51206	0.51212	0.5120				0.5120		0.51213

* FeO_t = FeO + Fe₂O₃

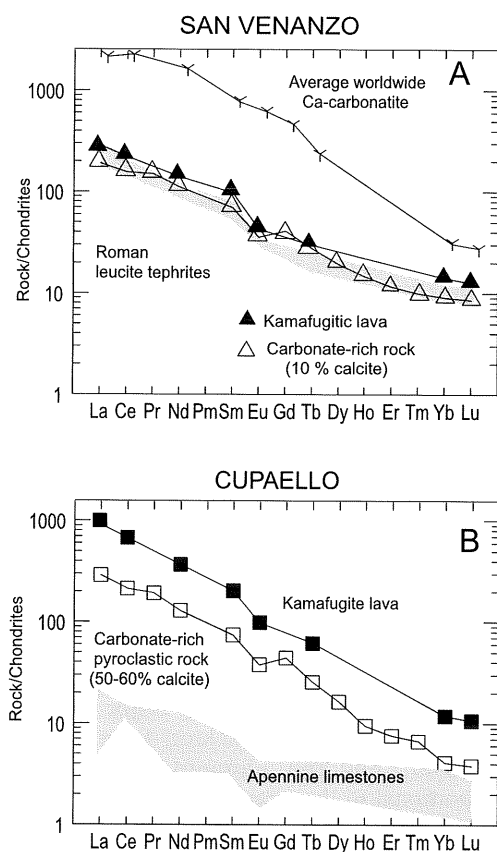


Fig. 2 – REE patterns of San Venanzo (A) and Cupaello (B) kamafugites and carbonate-rich pyroclastics. Patterns of ultrapotassic leucite tephrites from the Roman Province and limestones from northern Apennines are also shown. Source of data as in Table 1. Average Ca-carbonatite is from Woolley and Kempe (1989).

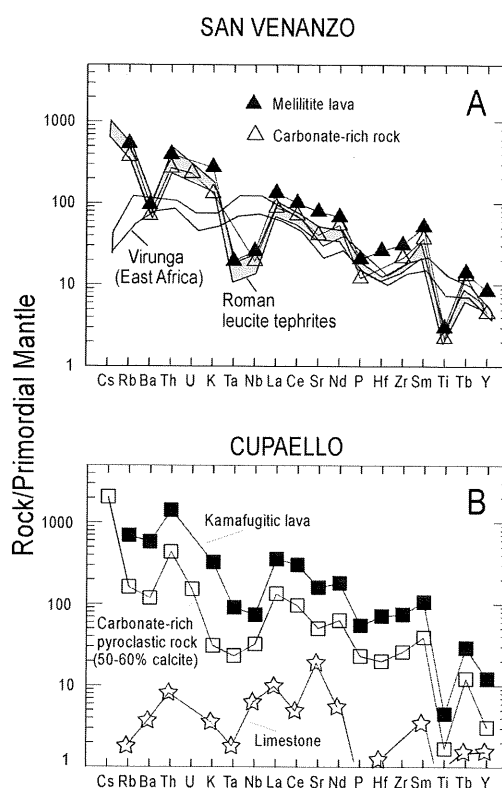


Fig. 3 – Incompatible element patterns normalized to primordial mantle composition (Wood, 1979) for San Venanzo (A) and Cupaello (B) lavas and carbonate-rich pyroclastics. Patterns of potassic mafic rocks from Karisimbi, Virunga volcanic district (Rogers *et al.*, 1992), Roman leucite tephrites and Mesozoic sedimentary carbonate rock are also shown. Source of data as in Table 1.

1. Their high concentrations of Large Ion Lithophile Elements (LILE);

2. An allegedly close similarity of Rare Earth Elements (REE) patterns to carbonatites;

3. The presence of calcite having high contents of Sr, Ba and other trace elements.

4. The presence of monticellite, Th-rich perovskite, zirconian schorlomite and other exotic minerals which are also found in carbonatites.

5. An alleged Sr-isotope equilibrium between carbonates and associated silicate phases,

which are said to dictate a common magmatic origin, such as by carbonate-silicate immiscibility.

6. Carbon isotope composition close to those of mantle-derived material ($\delta^{13}\text{C}$ around -5).

The following objections are raised to these points:

1. High LILE content is not exclusive to carbonatites. For instance, the LILE content of the ultrapotassic rocks of the Roman Province are comparable to, or higher, than those of the carbonate-rich rocks under consideration (Fig. 3).

2. The REE patterns for the Apennine

carbonate-rich volcanic rocks are highly fractionated in both REE and HREE, and have negative Eu anomalies (Fig. 2). These features are closer to ultrapotassic Roman Province rocks than to carbonatites. Stoppa and Woolley (1997) have noted that carbonatites do not normally have negative Eu anomalies, although some do.

3. The high trace element contents of some calcites are not exclusive to carbonatites. They have been found in calcite crystallized from hot carbonate-rich fluids. For instance, calcite in skarn xenoliths enclosed in calcalkaline dacite from the Lascar volcano, northern Chile show LREE enrichments up to 70 x chondrite, and HREE that closely match those of the host rocks (Mathews *et al.*, 1996). Calcite with high Sr and Ba occurs in skarn from the Alban Hills volcano (Federico and Peccerillo, 2002).

4. Minerals such as baddeleyite, Zr-rich garnet (~5% ZrO₂), Th-rich pyrochlore, REE-rich perovskite are not unique to carbonatites and have been reported from skarn xenoliths in the Alban Hills (Federico *et al.*, 1994; Federico and Peccerillo, 2002).

5. Data reported by Castorina *et al.* (2000) for carbonate and HCl-insoluble silicate fractions of carbonate-rich volcanic rocks show ⁸⁷Sr/⁸⁶Sr differences well outside analytical error. For instance, at Polino ⁸⁷Sr/⁸⁶Sr_{silicate} = 0.710793±9, ⁸⁷Sr/⁸⁶Sr_{calcite} = 0.710343±30 for sample PO2-5; in the Cupaello sample PPC-3d ⁸⁷Sr/⁸⁶Sr_{silicate} = 0.712113±16, ⁸⁷Sr/⁸⁶Sr_{calcite} = 0.710415±12. Clearly, the silicate and carbonate fractions are not in isotopic equilibrium.

6. Negative values of δ¹³C are commonly found in carbonates from skarns (e.g. Lattanzi *et al.*, 1980; Matthews *et al.*, 1996; Federico and Peccerillo, 2002).

While these objections do not disprove that the carbonate-rich volcanic rocks are carbonatites, they raise sufficient doubt to merit serious consideration of the alternative hypothesis of derivation from an interaction between silicate magmas and the wall rocks. Such an interaction is not restricted to bulk

rock assimilation but may include dissolution of carbonate from the volcanic conduit and re-precipitation, post-intrusion precipitation of carbonate from hot solutions, etc. (see Barker, 1993). Some factors that have to be discussed include:

1. Since the carbonate-rich volcanics and associated lavas have penetrated several thousand meters of Mesozoic to Miocene evaporites, limestones and marls, is it reasonable to exclude the possibility, indeed the strong probability, that these small-volume, single-pulse magmas will have reacted with them in some way?

2. Calcite from carbonate rich volcanic rocks have δ¹⁸O in the range +21 to +26 (Stoppa and Woolley, 1997). These δ¹⁸O values are away from those typical of carbonatites and are closer to compositions of sedimentary carbonates (Deines, 1989; Hoefs, 1997). High values of δ¹⁸O have been also found in calcite from lavas at San Venanzo (Turi, 1969).

3. The carbonate-rich volcanic rocks are depleted in several trace and major elements relative to the kamafugitic lavas *from the same volcano*, but the element depletion is proportional to their carbonate content. This is displayed for the examples of San Venanzo and Cupaello in Figs. 2, 3 and 4. At San Venanzo carbonate content is about 10% and the element abundances are about 10% less than in the overlying lavas. At Cupaello the calcite content is about 50% and the depletion is about 50% of that of the overlying lavas.

Granted, points (1) and (2), while strongly favouring a secondary origin for the calcite, do not prove it. It is possible, for example, that the passage of the silicate lavas through the crust was so rapid that there was no time for significant reaction. It is also well known that the oxygen isotope composition of many igneous rocks has been modified by post-crystallization exchange with ground water. But, it is clear from the high oxygen isotope ratios of fresh pyroxene and olivine of the silicate lavas (δ¹⁸O ranging from +12 to +14; Turi *et al.*, 1986; Author's unpublished data)

that the magmas have interacted with the wall rocks.

However, point (3) leaves no room for doubt. Element content depletion that is proportional to the calcite content of the rocks can not reasonably be generated in any other way than by dilution through incorporation of calcite that contained much lower element abundances than the silicate magmas. This does not fit the concept of the carbonatite-rich volcanic rocks being carbonatites, and supports the hypothesis of a secondary origin from sedimentary carbonate rocks. Any argument that, *on average*, the Umbria carbonate-rich volcanics have the same range of incompatible elements as the kamafugitic lavas is invalid, because comparisons must be between rocks erupted from the same volcano. This dilution effect is also seen in binary diagrams where element abundances are plotted against CaO, which, except for the amount occurring in the silicate lava (about 15 wt%), is a proxy of the calcite content. The carbonate-rich volcanics are on tie-lines that join kamafugitic lavas and barren carbonate material, such as the Apennine limestones (Fig. 4).

In the author's opinion point (3) is sufficient, by itself, to reject the carbonatite hypothesis. The epistemological basis of this conclusion is given in the Appendix.

GEODYNAMIC IMPLICATIONS

Interpretation of the carbonate-rich volcanics as belonging to a carbonatite suite has been used to argue that all the magmatism of central Italy represents an intraplate setting similar to east Africa (e.g. Lavecchia and Stoppa, 1996) and, hence, that deep mantle materials rather than subduction processes are responsible for compositional anomalies in this magmatism (e.g. Castorina *et al.*, 2000; Bell *et al.*, 2003). However, the carbonatitic nature of these rocks is at best questionable, and geochemical data strongly support subduction processes.

The central Italy kamafugitic lavas and associated pyroclastics bear a close resemblance

to the mafic lavas of the Roman Province in their content of incompatible trace elements, REE and Sr, Nd and Pb isotope ratios (Conticelli *et al.* 2002; Conticelli *et al.*, this issue). This suggests that all the igneous rocks of the central Apennines are derived from a compositionally similar upper mantle, which has been modified by the same type of metasomatizing agents. Consequently, the kamafugitic rocks and the

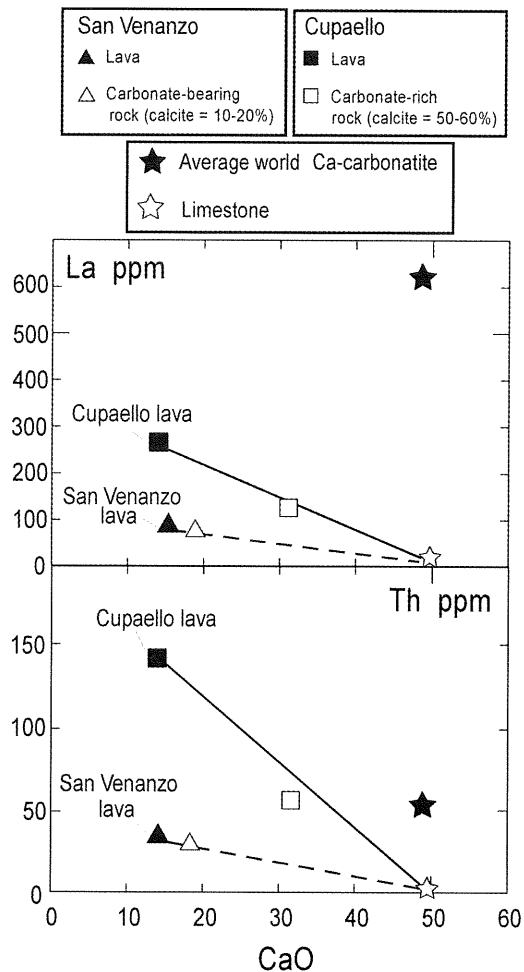


Fig. 4 – Variation diagrams of some trace elements against CaO for carbonate-rich pyroclastic rocks and associated lavas at San Venanzo and Cupaello. Increase in CaO is used as a proxy for increasing calcite contents.

Roman Province magmas have the same geodynamic significance.

The trace element characteristics of these rocks (high LILE/HFSE ratios) are typical of rocks associated with subduction zones. Moreover, they have fractionated incompatible element patterns with negative anomalies for Ba, Nb, Ta, Zr, Hf and Ti, which are typical of some upper crustal rocks such as granites and metapelites (see discussion in Peccerillo, 1999), and their radiogenic isotope compositions are closer to crustal than to mantle values (Peccerillo, 1999; 2002). Thus, all the ultrapotassic of central Italy have strong crustal-like signatures which are likely to be due to interaction between crustal and upper mantle components.

However, although wall rock assimilation has played an important role in some volcanoes, especially in monogenetic centres, the strong silica undersaturation and mafic composition of these rocks strongly limit the possibility of their having acquired these characteristics simply by wall rock assimilation. Discussion on this issue has been the focus of a wealth of papers (e.g. Peccerillo, 1995; Conticelli, 1998; Peccerillo, 2002) and will not be reiterated here. Therefore, it has been concluded that the crust was brought into the mantle (e.g. Holm and Munsksgaard, 1982; Peccerillo *et al.*, 1988; Conticelli and Peccerillo, 1992; Conticelli *et al.*, 2002; Conticelli *et al.*, this issue). The hypothesis of a derivation from a mantle contaminated by subduction-related upper crust is, in the author's opinion, best available explanation.

The timing of this subduction remains an open question and has been discussed by Peccerillo (2002). Geological and isotopic data support recent activity but this can not be considered proved simply by the weight of evidence in its favour.

CONCLUSIONS

The carbonate-rich volcanic rocks occurring in central Italy have been considered as carbonatites on the basis of a number of

evidences, such as exotic mineralogy and strong enrichment in LILE. However, there are several objections to this hypothesis, which can be summarised as follows:

a) the carbonate-rich pyroclastic rocks of the central Apennines consist of silicate and carbonate fractions;

b) worldwide carbonatites generally have high incompatible element contents, particularly REE;

c) the carbonate fraction of the Apennine carbonate-rich pyroclastic rocks generates a depletion in all these elements relative to the overlying silicate lavas. Depletion is proportional to the calcite content, revealing a barren nature for carbonate fraction;

d) if the carbonate component of the Apennine rocks were of carbonatitic origin there should be a proportional enrichment of these elements rather than a depletion;

e) therefore, the calcite component must be from a relatively barren source, of which sedimentary carbonate rocks are the most, or even the only, feasible possibility.

These objections have been raised previously (Peccerillo, 1998), but have not been answered and have been reiterated here only because it has been repeatedly requested by the Editor of this journal. Whether or not these arguments will be considered in the future, should be essentially a concern of scholars involved in studies of Italian carbonate-rich volcanics.

APPENDIX

Some epistemological remarks

According to Karl Popper (1959), an hypothesis or a theory is «scientific» only if it is falsifiable, i.e. it can be made to conflict with a set of data or even a single datum. Scientific theories can be falsifiable but not verifiable. Stated another way, any theory can be corroborated by a large number of data, but this does not mean that the theory is true or even close to truth. In contrast, it can be proven to be false and falsification is *sine qua non* of a scientific theory: it represents a sort of demarcation between

science and non-science. When a theory is unable to account for even one single conflicting evidence, it should be modified or rejected

Although the scientific rigour of Popperian falsificationism is very strict, it is hardly applicable to Earth Sciences. In Geology, conclusive evidence is rare and contrasting scientific theories generally stand side by side for a long time. In some cases one theory lags badly behind and is overcome by a competing theory; but it is not uncommon for old theories to stage a comeback. Crucial data or experiments rarely exist in Geology, and theories are abandoned not that much on the basis of falsifying experiments or data, but rather when there is another theory that becomes a better pigeonhole for the bulk of knowledge, i.e. it solves more problems and in a better way than its predecessors. Therefore, the Lakatos «research program» is a more appropriate methodology to heuristics in Earth Sciences than Popperian falsificationism (Lakatos, 1970).

However, falsificationism can be usefully applied to single problems in geology, and, in the author's opinion, the controversy over carbonate-rich rocks might be tested through such a methodology. This is to say that the hypothesis that the carbonate-rich rocks represent carbonatites, is indeed a scientific theory, in the Popper's meaning. Therefore, it can be falsified i.e. it can be made to conflict with some accepted basic statements. This implies that efforts should be directed not so much at finding corroborating evidence but rather to search for those statements that do not fit the theory. Evidence that can be considered for falsification purposes is the decrease of elemental abundances in carbonate-rich rocks with increase carbonate content. It is well known that worldwide carbonatitic magmas are very enriched in incompatible elements, especially REE (Fig. 2). The carbonate-rich rocks under study consist of a silicate portion and of a carbonate fraction (Stoppa and Woolley, 1997). If the latter is carbonatitic in nature, its increasing amount in the rock should produce an increase in incompatible element concentrations, especially REE. Instead, the presence of carbonate has a diluting effect in the rocks and element concentrations decrease with increasing calcite contents. This causes carbonate-rich rocks with 50 vol% carbonates to have about half the concentration of incompatible elements as pure silicate lavas occurring in the same volcano (Fig. 2b, 3b). As stated earlier, this inevitably

implies that the carbonate fraction is geochemically barren and acts as a diluter of the silicate melt. This does not fit the hypothesis that the carbonate material occurring in the carbonate-rich pyroclastic rocks is carbonatitic.

According to Hilary Putnam (1974), a false prediction of a theory may not depend on the theory itself, but rather on some auxiliary statements connected to the theory. Consequently, the statement rather than the theory should be modified or rejected. In the case under study, the auxiliary statement is that all primary carbonatites are enriched in incompatible elements (especially REE) and geochemically barren igneous carbonatites do not exist. If this statement will not be falsified, then the conclusion will be that the Italian carbonate-rich rocks cannot be carbonatites but are carbonated rocks. If the auxiliary statement will be proven to be false, the carbonatite hypothesis for Italian rocks could be saved.

In conclusion, the carbonatite hypothesis has been a new idea whose implication for geodynamics of the Apennines may be enormous. New theories and ideas should be regarded as precious, even when they seem a bit wild. However, we should not be eager to place excessive enthusiasm on the new theory simply because it is new. Once a new theory emerges, it must be open to criticism and the first ones to start with this game should be those who propose the theory. As Popper said «By criticizing our theories we can let our theories to die in our stead».

ACKNOWLEDGMENTS

I express my deepest appreciation to Dan Barker, John Gittins, Eric Essene and an anonymous referee for their suggestions, correction and comments. Their criticism considerably contributed to improve the manuscript. The research on potassic and ultrapotassic magmatism from central Italy has been financially supported by the Italian CNR and by funds from the University of Perugia.

REFERENCES

- BARKER D.S. (1993) — *Diagnostic magmatic features in carbonatites: implications for the origins of dolomite- and ankerite-rich carbonatites*. S. Afr. J. Geol., **96**, 131-138.

- BELL K., CASTORINA F., ROSATELLI G. and STOPPA F. (2003) — *Large scale, mantle plume activity below Italy: isotopic evidence and volcanic consequences*. EGS-AGU-EUG Joint Assembly, 6-11 April 2003, Nice, Geophys. Res. Abstracts, **5**, 14217.
- BOWEN N.L. (1926) — The carbonate rocks from Fen area in Norway. *Am. J. Sci.*, **212**, 499-502.
- CASTORINA F., STOPPA F., CUNDARI A. and BARBIERI M. (2000) — *An enriched mantle source for Italy's melilitite-carbonatite association as inferred by its Nd-Sr isotope signature*. *Mineral. Mag.*, **64**, 625-639.
- CONTICELLI S. and PECCERILLO A. (1992) — *Petrology and geochemistry of potassic and ultrapotassic volcanism from Central Italy: inferences on its genesis and on the mantle source evolution*. *Lithos*, **28**, 221-240.
- CONTICELLI S. (1998) — *The effect of crustal contamination on ultrapotassic magmas with lamproitic affinity: mineralogical, petrological and isotope data from the Torre Alfina lavas and xenoliths, Central Italy*. *Chem. Geol.*, **149**, 51-81.
- CONTICELLI S., D'ANTONIO M., PINARELLI L. and CIVETTA L. (2002) — *Source contamination and mantle heterogeneity in the genesis of Italian potassic and ultrapotassic volcanic rocks: Sr-Nd-Pb isotope data from Roman Province and Southern Tuscany*. *Mineral. Petrol.*, **74**, 189-222.
- CONTICELLI S., MELLUSO L., PERINI G., AVANZINELLI R., and BOARI E. (2004) — *Distribution and genesis of the potassic-ultrapotassic magmatism of central Italy*. *Per. Mineral.*, this issue.
- DEINES P. (1989) — *Stable isotope variations in carbonatites*. In: Bell K. (editor), *Carbonatites. Genesis and Evolution*. Unwin-Hyman, p. 301-359.
- FEDERICO M. and PECCERILLO A. (2002) — *Mineral chemistry and petrogenesis of granular ejecta from the Alban Hills volcano (Central Italy)*. *Mineral. Petrol.*, **74**, 223-252.
- FEDERICO M., PECCERILLO A., BARBIERI M. and WU T.W. (1994) — *Mineralogical and geochemical study on granular xenoliths from the Alban Hills volcano (Central Italy): bearing on evolutionary processes in potassic magma chambers*. *Contrib. Mineral. Petrol.*, **115**, 384-401.
- GALLO F., GIAMMETTI F., VENTURELLI G. and VERNIA L. (1984) — *The kamafugitic rocks from San Venanzo and Cupaello, central Italy*. *Neues Jb. Mineral., Monatsh.*, 1984, 198-210.
- HOEFS J. (1997) — *Stable isotope geochemistry*. Springer, Berlin, 201 pp.
- HOLM P.M. and MUNKSGAARD N.C. (1982) — *Evidence for mantle metasomatism: an oxygen and strontium isotope study of the Vulsinian district, central Italy*. *Earth Planet. Sci. Lett.*, **60**, 376-388.
- LAKATOS I. (1970) — *Falsification and the methodology of research programmes*. In: Lakatos I. and Musgrave A. (editors), *Criticism and growth of knowledge*, Cambridge University Press, Cambridge, pp. 91-196.
- LATTANZI P., RYE D.M. and RICE J.M. (1980) — *Behaviour of ¹³C and ¹⁸O in carbonates during contact metamorphism at Marysville, Montana: implications for isotope systematics in impure dolomitic limestones*. *Am. J. Sci.*, **280**, 890-906.
- LAVECCHIA G. and STOPPA F. (1996) — *The tectonic significance of Italian magmatism: an alternative view to the popular interpretation*. *Terra Nova*, **8**, 435-446.
- LENTZ D.R. (1999) — *Carbonatite genesis: A reexamination of the role of intrusion-related pneumatolytic skarn processes in limestone melting*. *Geology*, **27**, 335-338.
- MATTHEWS S.J., MARQUILLAS R.A., KEMP A.J., GRANCE F.K. and GARDEWEG M.C. (1996) — *Active skarn formation beneath Lascar Volcano, northern Chile: a petrographic and geochemical study of xenoliths in eruption products*. *J. Metam. Geol.*, **14**, 509-530.
- MELLUSO L., CONTICELLI S., D'ANTONIO M., MIRCO N.P. and SACCANI E. (2003) — *Petrology and mineralogy of wollastonite- and melilitite-bearing paralavas from the Central Appennines*. *Am. Mineral.*, **88**, 1287-1299.
- PECCERILLO A., POLI G. and SERRI G. (1988) — *Petrogenesis of orenditic and kamafugitic rocks from Central Italy*. *Canad. Mineral.*, **26**, 45-65.
- PECCERILLO A. (1995) — *Mafic calcalkaline to ultrapotassic magmas in central-southern Italy: constraints on evolutionary processes and implications for source composition and conditions of magma generation*. *Proceedings of Intern. Symp. Upper Mantle, Sao Paulo, Acad. Brasil. Sci.*, **67**, 171-189.
- PECCERILLO A. (1998) — *Relationships between ultrapotassic and carbonate-rich volcanic rocks in Central Italy: petrogenetic implications and geodynamic significance*. *Lithos*, **43**, 267-279.
- PECCERILLO A. (1999) — *Multiple mantle metasomatism in central-southern Italy: geochemical effects, timing and geodynamic implications*. *Geology*, **27**, 315-318.
- PECCERILLO A. (2002) — *Quaternary magmatism in Central-Southern Italy: a new classification scheme for volcanic provinces and its geodynamic implications*. *Boll. Soc. Geol. It., Vol. Spec. N. 1*, 113-127.
- POPPER K. (1959) — *The logic of scientific discovery*. Hutchinson, London. Translation to

- Italian. Logica della scoperta scientifica, Einaudi, Torino p. 549.
- PUTNAM H. (1974) — *The «corroboration» of theories*. In: Hacking I. (editor), *Scientific Revolutions*, Oxford University press, Oxford, pp. 60-79.
- ROGERS N.W., DE MULDER M. and HAWKESWORTH C.J. (1992) — *An enriched mantle source for potassic basanites: evidence from Karisimbi volcano, Virunga volcanic province, Rwanda*. *Contrib. Mineral. Petrol.*, **111**, 543-556.
- SAHAMA T.G. (1974) — *Potassium-rich alkaline rocks*. In: Sorensen H. (editor), *The alkaline rocks*. John Wiley, London, 94-109.
- STOPPA F. and LAVECCHIA G. (1992) — *Late Pleistocene ultra-alkaline magmatic activity in the Umbria-Latium region: an overview*. *J. Volcanol. Geotherm. Res.*, **52**, 277-293.
- STOPPA F. and WOOLLEY A.R. (1997) — *The Italian carbonatites: field occurrence, petrology and regional significance*. *Mineral. Petrol.*, **59**, 43-67.
- TURI B. (1969) — *La composizione isotopica dell'ossigeno e del carbonio dei carbonati presenti nelle vulcaniti di San Venanzo (Umbria)*. *Per. Mineral.*, **38**, 589-603.
- TURI B., TAYLOR H.P. and FERRARA G. (1986) — *A criticism of the Holm-Munksgaard oxygen and strontium isotope study of the Vulsinian district, central Italy*. *Earth Planet. Sci. Lett.*, **78**, 447-453.
- WOOD D.A. (1979) — *A variably veined suboceanic upper mantle. Genetic significance for mid-ocean ridge basalts from geochemical evidence*. *Geology*, **7**, 499-503.
- WOOLLEY A.R. and KEMPE D.R.C. (1989) — *Carbonatites: nomenclature, average chemical composition and element distribution*. In: Bell K. (editor), *Carbonatites. Genesis and Evolution*. Unwin-Hyman, 1-14.

