REPLY TO: COMMENT TO: "VOLCANIC ACTIVITY FROM THE NEOGENE TO THE PRESENT EVOLUTION OF THE WESTERN MEDITERRANEAN AREA. A REVIEW" BY MICHELE LUSTRINO

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We recently published a review of geochemical data on volcanic products emplaced during the last 30 Ma in the western Mediterranean area (Lustrino, 2000a). In this paper, the most recent petrogenetic models proposed for various igneous provinces were compared each other and tentatively fitted in a geodynamic scenario of evolution. The aim of that paper was to furnish an updated review of the petrologic models proposed to explain the origin of the main volcanic outcrops of Spain, France, Morocco and Italy, with special emphasis given to the Plio-Pleistocene volcanic rocks of Sardinia. The choice to focus on the recent volcanic activity of Sardinia was thought because of its geographic position (Sardinia represents a lithospheric slice in between two oceanic areas reworked during Hercynian and Alpine orogeneses), its peculiar trace element composition (Plio-Pleistocene volcanic rocks of Sardinia show the highest Ba/Nb and one of the lowest Ce/Pb and Nb/U among the entire Cenozoic European Volcanic Province anorogenic products) and its unique Sr-Nd-Pb isotopic signature ($^{87}Sr/^{86}Sr$ close to bulk Earth values, ε_{Nd} ~ -5, $^{206}Pb/^{204}Pb$ down to ~ 17; Lustrino et al., 2000).

The comments of Elter seem to not take in consideration the true subject of our paper (geochemistry of 30-0 Ma volcanic rocks) and are entirely focused on the Hercynian geodynamic evolution of Western and Southern Europe. According to Elter, we presented a "continuous" model from Hercynian time to the present, but this is not the case. We don't present any continuous model: on trace element and Sr-Nd-Pb isotopic grounds (data published elsewhere; Lustrino, 2000c; Lustrino et al., 2000) we simply suppose a relationship between processes responsible for the geochemical signature of mantle sources of Plio-Pleistocene volcanic rocks of Sardinia and those occurred in late Paleozoic, mainly during post-collisional extensional movements. Now we are going to reply to his doubts about the scientific valence of our paper (Lustrino, 2000a); in particular, we will follow its own scheme.

Trend of Hercynian subduction

Before the continent-continent collision between Laurussia and Gondwana (Hercynian Orogeny s.s.) large amounts of oceanic crust were consumed in subduction processes (e.g., Tait et al., 1997); however, the polarity of such a Hercynian subduction system is still debated. Geochemical evidences for subduction processes have been considered the Hercynian calcalkaline and ultrapotassic to shoshonitic magmatism throughout Europe (e.g., Turpin et al., 1988; Shaw et al., 1993; Tommasini et al., 1995; Finger et al., 1997; Wenzel et al., 1997).

Elter evidences two main hypotheses with regard to the polarity and the style of subduction of the Rheic ocean and wonders that these hypotheses are not discussed in our paper (Lustrino, 2000a) and not shown in Fig. 4 of the same paper. However, Elter simplifies too much this topic. Before Hercynian Orogeny s.s., huge oceans separated Gondwana from Laurussia. This last supercontinent was assembled only by the Late Devonian, after the Iapetus Ocean, Tornquist Sea and Rheic Ocean (separating Baltica from Laurentia, Baltica from Avalonia and Avalonia from Armorica, respectively) were all closed (McKerrow et al., 1991; Tait et al., 1997; Golonka, 2000). Only after the total consumption of the Massif Central-Moldanubian Ocean (separating Laurussia from Gondwana) did the true Hercynian Orogeny s.s. (i.e., continent-continent collision) take place (see Golonka, 2000 and Lustrino, 2000b, for a review).

The European Hercynian Belt is, therefore, characterized by, at least, two suture zones: the *northern suture zone*, that can be found between northern Britain and Cornwall, the northern Phyllite Zone and the French section of the Hercynian zone along the Bray dextral fault; this suture zone is characterized by roughly south directed subduction of oceanic crust (e.g., Faure et al., 1997; Tait et al., 1997) On the other hand, the *southern suture zone*, testifying the closure of the Massif Central-Moldanubian Ocean in between Gondwana and Laurussia, is much less easily identified because of rarer remnants. To this suture zone (southern) the Posada-Asinara Line belongs.

The southward closure of the Rheic Ocean is, therefore, not in contrast with that shown in Fig. 4 of Lustrino (2000a): what is shown in that figure is simply the north-directed subduction system of the southern suture zone of European Hercynides (Matte, 1991) and not the south-directed subduction system of the northern suture zone (e.g., Tait et al., 1997).

Obviously, Fig. 4 is a simplification of the Hercynian processes in Southern Europe in correspondence of Sardinia. This figure wants only to illustrate to scientists non-skilled and non-expert of Hercynian age geodynamics a simplified interpretation (based on several data reported, i.a., by Burg et al., 1987; Cappelli et al., 1992; Carmignani et al., 1994) of the probable Paleozoic evolution of Sardinia.

Moreover, Elter cites a paper of Carmignani et al. (1979), according which the polarity of subduction of the Rheic Ocean was southwards, with Corsica in foreland and Sardinia in interland in palinspastic reconstruction. However, Carmignani et al. (1979) absolutely don't cite any southwards subduction of Corsica basement below Sardinia; on the contrary, they favor the hypothesis according which Sardinia represents the foreland of the Hercynian subduction system. These authors only are in favor for a continental rather than oceanic origin for the basic protolith of the granulites and eclogites of NE Sardinia and SW Corsica. The absence of ophiolitic remnants, the (interpreted) continental nature of the basic rocks and the abundance of granitoids of crustal origin, allowed Carmignani et al. (1979) to consider the Sardo-Corsican tectonism completely ensialic. Also in this contest (now rejected by the same authors group; Carmignani et al., 1994; Carmignani and Oggiano, 1999), the polarity of subduction remains northeastward, with stacking of Gondwana margin (i.e., Sardinia) beneath the Armorican plate (i.e., Corsica).

We repeat that the aim of our paper was not to fully describe the entire structural and petrological models of evolution of European Hercynides. Any (better documented and better constrained) review paper by Elter will be certainly well accepted by the scientific community in order to clarify such debated topics.

The Hercynian geodynamic interpretation in the Sardinia - Corsica basement

Elter wonders that we did not cite any references with regard to the Posada-Asinara Line (which is thought to be the southeastern expression of the leptyno-amphibolitic group cropping out in the Massif Central; e.g., Elter et al., 1990; Matte, 1991) in north Sardinia. However, the reader is pleased to consult Lustrino (2000b) where we consider, with slight more detail, this argument and where it is possible to find more detailed information and more numerous references.

The Posada-Asinara Line has not been involved in recent evolution since Permo-Triassic time, but this is not in contrast with the model we propose (Lustrino, 2000a; Lustrino et al., 2000). We really do not understand where our model is supported by wrong interpretation. We never have thought that the Posada-Asinara Line could have been reworked in following orogenies!

The open question about the significance of the Hercynian basic rocks

Elter reprimands us to do not give the right weight to the open question of the origin of Hercynian basic rocks. Probably Elter really does not understood the significance of our paper. The goal of our paper published on Ofioliti was not to solve the geodynamic significance of basic rocks of the Southern Europe Hercynian chain or to be in favor of the monocyclic instead of policyclic model, but was much more humbly: to offer to a reader not expert in the field of igneous petrology, an updated review of the most recent papers dealing with the last 30 Ma volcanic activity of Spain, France, Morocco and Italy.

The role of the rotation of the Sardinia - Corsica blocks

For this point we repeat that wrote above. The sketch presented in Fig. 4 of Lustrino (2000a) aims only to give a general scheme of evolution, well knowing the oversimplification adopted. To consider the possibility of a ~125° clockwise rotation of the Sardinia-Corsica block during the upper Stephanian-early Autunian (~290 Ma), as recently proposed by Edel (2000), does not change the significance of that Figure. In both the cases (i.e., with or without clockwise rotation of Sardinia during Late Paleozoic) the polarity of subduction has been proposed towards Corsica (Cappelli et al., 1992; Carmignani et al., 1994; Carmignani and Oggiano, 1999; Edel, 2000), and thus in agreement with Fig. 4.

The tectonic framework in Late Carboniferous - Early Permian time

Many are the evidences for extensional tectonic context during Late Carboniferous-Early Permian times (e.g., Gardien et al., 1997; Cortesogno et al., 1998; Hegner et al., 1998); on the other hand, the presence of Upper Carboniferous (~ 300-290 Ma) calcalkaline, geochemically subduction-related volcanic rocks in southwestern Germany (Saxothuringian area) could be an evidence of the diachronous closure of oceanic domains within the Hercynian orogenic belt (Schmidberger and Hegner, 1999). The presence of microplates between Europe and North Africa and the opening of back arc oceans in active margins resulted in a non-synchronous closure of the western proto-Tethys Ocean (Ziegler, 1986; Stampfli, 1996). The complete closure of the Paleotethyan domain was not fully achieved in SE Europe during the Late Carboniferous; moreover, this domain lasted up to Permian in the Hellenides and even in Triassic times more to the East (Kazmin, 1991; Stampfli, 1996). Moreover, whereas an Upper Ordovician-Middle Devonian subduction-related geodynamic setting is favored within European Hercynian belt (e.g., Ziegler, 1992; Martinez-Catalan et al., 1997), in Sardinia an igneous activity consisting of alkali to tholeiitic basaltic suites, with within-plate affinity, is reported (Memmi et al., 1983). The existence of coeval compressive (subduction of oceanic plates or continent-continent collision) and extensional (post collisional movements with formation of intermontane troughs ad widespread uplifts as well as pull-apart basins) tectonic settings is, therefore, apparent.

That shown in Fig. 4b of Lustrino (2000a) is, clearly, a simplification of the possible framework of European Hercynides. The Late Carboniferous-Early Permian reconstruction shown in Fig. 4b evidences the ongoing isostatic instability of the overthickned lithospheric keel during late- to post-compressional phases of the Hercynian collision; the Late Permian reconstruction, even in Fig. 4b, evidences the well developed extensional stages reached in European Hercynides, and not, as Elter thinks, the first phases of the extensional event. Of course, we did not mention the huge bibliography existent for such a time interval because that was not the place where discuss this argument; however, it is possible to find some of them cited in Lustrino (2000b; 2001).

The post-collisional sinking of the lithospheric root during late Permian

The post-orogenic collapse of the Hercynian belt is thought to be caused by delamination and detachment of the lithospheric root (Bonin et al., 1998; Meissner and Mooney, 1998). Partial melts from the ascending asthenospheric mantle diapir, whose emplacement was facilitated by crustal extension and relative lithospheric thinning, therefore caused high-T/low-P regional metamorphism (Gardien et al., 1997), producing the group II granulites of Pin and Vielzeuf, (1983), large volumes of bimodal volcanism and mainly anatectic plutonic emplacement during Late Carboniferous-Early Permian (Azevedo and Nolan, 1998; Gaeta et al., 2000). The density increase of the lithospheric root may led to gravitational instability with negative buoyant forces; the keel accreted in continent-continent collisional zones may, under its own weight, collapse and detach from the overlying crust. Many are the lines of "evidence" that led several authors to believe recycling of lower crust into the mantle and these have been recently summarized by Lustrino (2001): *1)* negative anomalies of Eu, Sr and transition metal in continental crust estimates. These evidences have been related to detachment of a plagioclase-rich cumulate, lost from the base of the crust and recycled into the mantle (Gao et al., 1998); *2)* the apparent paradox of major element composition of total continental crust which is more differentiated (i.e. andesitic l.s.) than mantle partial melts (i.e. basaltic l.s.). The more evolved nature can be explained in terms of intracrustal differentiation, responsible for the formation of more acid upper crust and recycling of mafic residual counterpart (lower crust) into the mantle (Rudnick, 1995); *3)* anomalous composition of upper Archean syenites of Australia related to delamination by convective thinning of a dense, garnet-rich, lower crust (Smithies and Champion, 1999); *4)* trace element and Sr-Nd-Pb isotopic composition of Plio-Pleistocene volcanic rocks of Sardinia. The genesis of these volcanic rocks has been modeled with digestion of lower amount of lower crustal lithologies at mantle depths (Lustrino et al., 2000); *5)* trace element and Sr-Nd-Pb isotopic modeling of continental crust and Enriched Mantle I end-member (Tatsumi, 2000); *6)* anomalous heat flow and low crustal thickness under continental collisional zones (Gao et al., 1998); *7)* experimental petrology studies carried out on lower crustal lithologies. In particular these studies (e.g., Wolf and Wyllie, 1994) have shown the possibility of delamination of such a layer if metamorphic reaction change the original paragenesis from amphibolitic (with density ~3 g/cm^3) to garnet-bearing granulite or eclogite (with density ~3.5-3.8 g/cm^3); *8)* numerical modeling of collisional processes (Schott and Schmelling, 1998; Arnold et al., 2001). The results led to the interpretation of the possibility of delamination and subsequent detachment of the mantle lithosphere in a relatively short geological time scale (in the order of 3 Ma), in agreement with the observed short time scale of uplift and exhumation (e.g., Willner, 1998).

We agree with Elter when he says that inferring a tectonic setting mainly on the basis of geochemical constrains may fail and that a comprehensive consideration of the whole geological-structural, petrological and geodynamic knowledge on the geological context of in interest is highly needed (Lustrino, 2001). Indeed, it is well known that partial melts with substantial compositional differences can originate from the same source, and the same melts can be generated in different tectonic settings.

In summary, we believe that the doubts of Elter about the inadequacy of treatment of some main topics in our paper (Lustrino, 2000a) can be easily solved, being these negligible or, better, non-existent at the present day state of the art.

Best wishes.

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