

## VOLCANISM AS A TRACER IN GEODYNAMIC PROCESSES

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## ABSTRACT

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The use of volcanological studies in the reconstruction of geodynamic processes is discussed, pointing out that a valuable contribution only follows from a critical evaluation of all available data. Any simplistic generalization that is based on a too fragmentary knowledge of the topic under discussion, leads to completely erroneous conclusions and suggests models that hardly fit a more general geological picture. Volcanological data actually contribute to a better knowledge, if the research that aims to understand the mechanism of magma origin and ascent strictly avoids any kind of constraining dogmatic premises.

## INTRODUCTION

A striking result obtained by earth scientists in the last fifty years is the reconstruction of geodynamic processes that affect the evolution of the surface of our planet. This result is essentially due to the complementary character of the scientific contributions which allow the proposed models to be compared and mutually checked.

Within these reconstructions there are, of course, substantial assumptions that are based on extrapolations of geophysical data obtained in areas where geodynamic processes are in progress. This consideration mainly concerns deep-seated processes in the lower lithosphere and the asthenosphere. Moreover, it is commonly accepted that magmas mostly originate at those depths.

The obvious consequence from the above considerations is that the study of the evolution of volcanism, in space and time, offers very important clues to help recognise the various tectonic phases that produced the present structure of a region.

## VOLCANISM AND TECTONIC SETTING

Already at the beginning of our century BECKE (1902) had recognised the very important relation that exists between the petrography of igneous rocks and their tectonic setting. Consequently he proposed a subdivision of these rocks into two main groups; those that occur in folded and those that occur in faulted regions. He introduced the terms of 'Pazifische Sippe' and 'Atlantische Sippe' and referred, beyond any doubt, to the structural character of the Pacific (folded) and the Atlantic (faulted) margin.

But the real meaning of this distinction was largely misunderstood and the proposed terminology harshly criticized, erroneously interpreting it in a geographical sense (DALY, 1914). Thus Becke's important discovery of the relation between volcanism and tectonics was consigned to oblivion to such a degree that forty years ago nearly all geologists believed the Mid-Atlantic Ridge to be a folded mountain chain and rejected the suggestion that the 'atlantic character' of the volcanic products indicates a tensional tectonic setting (RITTMANN, 1939). Twenty years later oceanographic investigations proved the suggestion to be correct (HESS, 1962; VINE & MATTHEWS, 1963).

The most typical appearance of a tectonic environment

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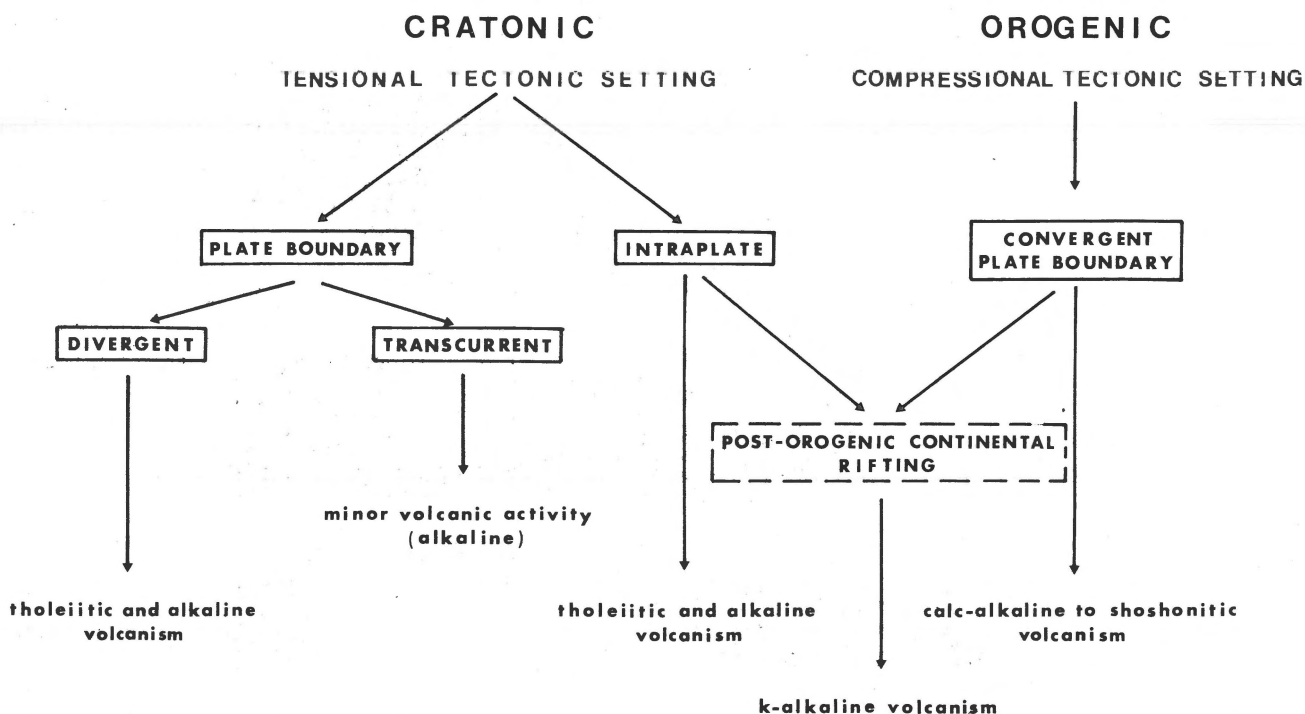


Fig. 1

Tectonic setting and magma-series. A schematic proposal to stress the main relationships between regional tectonics and magmatic affinity.

dominated by a tensional stress field, is represented by mid-oceanic or spreading ridges, but tensional tectonics are active also in continental areas.

A subdivision of volcanism based on the geographical distribution of its products in oceans and continents surely leads astray. Sophisticated statistics of petrochemical data according to this simplistic concept may produce 'mathematically correct' results which, however, are valueless and even misleading from the magmatological and geological point of view, because they lack a critical evaluation of the input data.

Furthermore, care should be taken to avoid the insertion of altered-rock analyses into the statistical sample, which would change the conclusions substantially. Hence an accurate microscopical examination of the analysed rocks is necessary in order to verify the presence of secondary minerals due to autopneumatolysis, autohydrothermalization, weathering, wall-rocks contamination or other processes that may alter the chemical composition of the original igneous rock.

Volcanic rocks which are typical of areas dominated by a tensional tectonic setting and particularly those from oceanic rifts, belong to the tholeiitic and Na-alkaline series (CANN, 1971; THOMPSON, 1973; BASS ET AL., 1973; SCHILLING, 1971; SHIDO ET AL., 1971; THOMPSON ET AL., 1972; HEKINIAN & AUMENTO, 1972). The alternating occurrence of alkaline and subalkaline rock series and the differentiation stage of their members are mainly conditioned by the dynamics that locally prevail at the boundary between interacting lithosphere segments. A rapid distension that causes the opening of abyssal

fissures favours the eruption of tholeiitic magmas (axial zones of oceanic rifts), while a slower distension leads to the formation of alkaline magmas (HEKINIAN & AUMENTO, 1972; SCHILLING, 1973), with a frequent recurrence of highly differentiated products (HEKINIAN, 1974).

Volcanics from continental faulted areas mostly show a distinct alkaline character, but are often associated with tholeiitic and transitional types (BARBERI ET AL., 1974-a; BARBERI & VARET, 1974; VILLARI, 1974).

Particularly noteworthy is the K-alkaline volcanism, associated with continental rifts and grabens (BAILEY, 1974). The peculiar meaning of these magmatic associations needs a more specific discussion. It should, however, be pointed out that the complexity of the continental environments accounts for significant variations in any rigid model that aims at the generalization of the common characters of the volcanism.

In contrast with areas dominated by tensional tectonics, folded regions are characterized by the occurrence of volcanic products with a distinct calc-alkaline affinity. In these compressional tectonic environments (as for tensional environments) the volcanic series also often exhibit relevant compositional variations (JAKES & WHITE, 1972; EWART, 1976; JAKES & GILL, 1970). Among the most apparent aspects of this chemical variability, is the difference in  $K_2O$  enrichment, that matches the space and time distribution of volcanic products (DICKINSON, 1972). The occurrence of high-K and shoshonitic rock series is actually confined to the mature stage of the orogenic volcanism and/or they usually develop farther backward from the volcanic front.

Island arcs and continental margins of cordilleran type are in a structural environment characterized by the occurrence of this orogenic volcanism which, in spite of its extremely variable alkalinity (mainly affected by the  $K_2O$  content), is largely dominated by calc-alkaline products. Widespread acid volcanics (mostly ignimbrites), resulting from the partial melting of the upper continental crust, are also frequently reported as a further characterization of continental margins (EWART & STIP, 1968; PICHLER & KUSSMAUL, 1972).

An overview of the above considerations in terms of global tectonics, is given in figure 1.

From the described relationships between active volcanism and present structural settings, it follows that there is a need for a critical review of those parameters which are commonly used as discriminating factors, in particular where ambiguity may arise.

#### BIMODALITY OF MAGMAS AND DISCRIMINATING CRITERIA

To establish the tight relationship that exists between volcanism and regional tectonics in its antithetical behaviour (tensional and compressional), we have to look for discriminating parameters that enable a distinction of autonomous categories of magmas. These parameters should be irrespective of their geographical distribution in oceans or continents. In other words, it is necessary to empirically demonstrate a marked bimodality of volcanism.

Any such discriminating factor is all the more efficient when the distribution curve of relevant rock properties shows two well-separated maxima. Among the volcanic phenomena the most suitable one stressing the bimodality of the volcanic activity is the explosive character of magmas, which can be expressed by the index  $E = \text{tephra} / (\text{tephra} + \text{lavas})$  (RITTMANN, 1930). As banal as the determination of  $E$  may appear, the following remarks must be kept in mind in order to avoid erroneous estimates of the magmatic explosivity.

The phenomena exhibited by single eruptions (particularly by weak ones) are frequently modified by occasional, local conditions and therefore they do not characterize the general behaviour of a volcanic complex. Accordingly it is advisable to carry out a careful stratigraphic survey of the whole area, to specify the nature and distribution of pyroclastic products. Depending on the force of ejection and the ease of reworking, pyroclastics generally cover a wide area beyond the boundary of the volcanic edifice. They often form a discontinuous and thin layer that permits only rough estimates of their volume. The amounts of tephra ejected by highly explosive eruptions are consequently underestimated in most cases. On the other hand too much attention is generally drawn to the explosive activity of historical volcanic eruptions, which are mostly reported by occasional and/or distant observers or chroniclers. The spectacular ejection of pyroclastics is obviously the most impressive aspect of an eruption

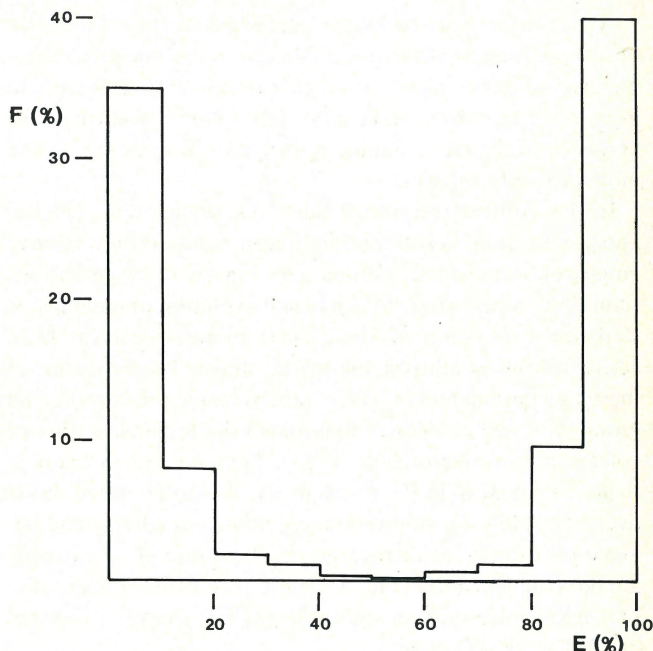


Fig. 2  
Frequency (F) distribution of magmatic explosivity index  $E = \text{Tephra} / (\text{Tephra} + \text{Lavas})$ . F is expressed as total volume %. Ejecta by phreatic or hydromagmatic vapour explosions are strictly discarded.

to be reported, while the quiet outflow of even huge volumes of lava is hardly mentioned, if ever.

Another important aspect is the frequent phreatic and hydromagmatic explosive activity, due to the sudden vaporisation of ground- and sea-water, due to abrupt heat transfer from rising magmas. Such vapour explosions are obviously not related to a primary character of the magma, but they depend upon the interaction of the magmas with the shallow environment. Their products should not be taken into account for a correct estimate of the explosivity index ( $E$ ).

The histogram of the  $E$  index (RITTMANN, in press) (Fig. 2), reveals the bimodality of volcanic activity extremely well.

The search for discriminating parameters to recognise volcanic products of different magmatic affinity has for a long time been focussed on chemical and geochemical characteristics. The mere mineralogical composition of volcanic rocks is in fact inadequate for such a distinction as it depends, apart from the chemical composition, on the physical conditions that prevailed during the consolidation of magma. The commonly adopted chemical parameters have very often shown their limitations for a correct distinction between cratonic and orogenic associations of magmas. Further ambiguities may arise sometimes from the indiscriminate application of the so-called differentiation indices which are based on the implicit assumption that any magmatic evolution is to be merely ascribed to fractional-crystallization processes.

According to present knowledge, the conclusions that one may draw suggest that none of the proposed chemical parameters can be singularly used as a discriminating factor. In most cases, a correct indication only follows from the convergence of all the available information that points to the most probable solution.

In this context the use of the  $\tau^1$  vs.  $\sigma^1$  diagram<sup>2</sup> (Fig. 3) appears to be of substantial help as it is based on objective empirical statements, without any regard to dogmatic assumptions concerning the origin and evolution of magmas. A statistical evaluation of about 5000 analyses of lavas from active volcanoes all over the world, shows that by means of these two parameters ( $\tau^1$  and  $\sigma^1$ ) the volcanic products can be grouped in two categories that match the tectonic setting of volcanoes in orogenic belt (Fig. 3, field A) and in cratonic regions (Fig. 3, field B), respectively. It is to be noted, however, that plots for some sodic phonolites, trachytes and comendites from cratonic regions, overlap those of post-orogenic potassic volcanics (Fig. 3, field C). A more efficient distinction to solve such an ambiguity can be achieved by means of the  $K_2O/Na_2O$  ratio.

Some general considerations concerning the use of chemical parameters have to be stressed, if one wants to correctly define the magmatic affinity. The original composition of magmatic rocks is frequently altered by weathering, pneumatolytic and hydrothermal processes, reactions with seawater, etc. Intrusive rocks (dikes, sills, etc.), submarine products (pillows, hyaloclastites, etc.) and pyroclastics (pumices, ashes, ignimbrites, etc.) frequently undergo such an alteration. For magmatological studies most of the chemical analyses of the above mentioned products should be discarded, but not necessarily so for the characterization of petrographic provinces. Lavas, too, should be treated with caution because -mainly in the uppermost parts of lava flows- they may have been altered by fumarolic activity.

Rock analyses reported in the literature are unfortunately very often presented without an adequate petrographical description and/or indications about the geological occurrence of the samples. Thanks to sophisticated analytical techniques, the distribution of trace elements is mostly given, but they lack corresponding bulk analyses of the major elements. Isotopic ratios refer frequently to rocks merely characterized by a name that is based upon an unascertained nomenclature.

The above considerations -far from being a sterile critique of objective scientific and technological contributions- are meant to serve as an invitation to an objective evaluation of data and to reject categorically all dogmatic premises and simplistic models.

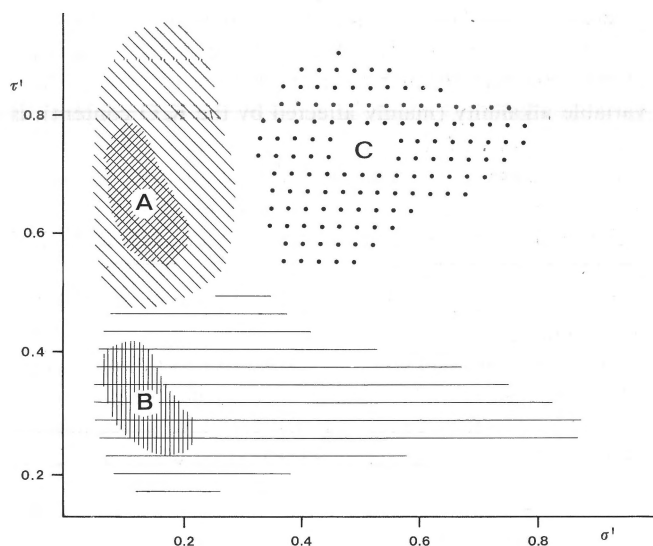


Fig. 3  
 $\tau^1$  vs.  $\sigma^1$  plots of about 5000 rock analyses from active volcanoes. Field A represents 98% of lavas from orogenic regions (90% within the cross-hatched area); field B represents 96% of lavas from cratonic regions (90% within the cross-hatched area). Lavas from post-orogenic subsiding areas (K-alkaline series) and some extreme differentiates of Na-alkaline series plot in field C.

## GEODYNAMIC EVOLUTION AND VOLCANISM

Both the time and space evolution of geodynamic processes are often extremely complex and a good approximation of their reconstruction is achieved only through mutually integrative investigations. Among these, the study of volcanism is of paramount importance by its two-fold role: as a check for the validity of a proposed model and as a hint to new hypotheses.

The indiscriminate application of badly digested concepts and/or the total ignorance of the geological environment where volcanism occurs, may lead to completely wrong conclusions that are masked by the scientific credibility of volcanological data. One of the most striking examples concerning the Mediterranean area, is offered by the interpretation in terms of plate tectonics suggested by NINKOVICH & HAYS (1972). The parameter which led to the suggestion of their model, is simply the relation between the geographical distribution of volcanics and the variation in average  $K_2O$  content. According to this relation Mt. Etna, the Aeolian Islands and Mt. Vesuvius are believed to belong to the same structure, dominated by subduction from Sicily to Naples. No attention has been paid to the geological, structural and geophysical features of the various regions where the volcanism evolved, which clearly shows fundamentally different magmatological characters (BARBERI ET AL., 1973, 1974-a, 1974-b). It is worth to remember that the volcanics of Mt. Etna belong to the tholeiitic-alkaline basaltic series, and are built up on a faulted continental crust, locally overlain by

<sup>2</sup>  $\sigma^1 = \sigma / (10 + \sigma)$ , wherein  $\sigma = (Na_2O + K_2O)^2 / (SiO_2 - 43)$  (Rittmann, 1959);

$\tau^1 = \tau / (10 + \tau)$ , wherein  $\tau = (Al_2O_3 - Na_2O) / TiO_2$  (Gottini, 1969).

gravity nappes from the metamorphic mountain range to the North (Peloritani Mts.). On the other hand, the volcanoes of the Aeolian Islands yielded calc-alkaline to shoshonitic products and developed on a folded metamorphic basement located on the opposite side of the Peloritani orogenic belt with respect to Mt. Etna. Finally, the volcanism of the Neapolitanian area is characterized by peculiar magmas of the potassic series, in agreement with its position in a subsiding continental area, affected by post-orogenic tectonic movements.

In other cases the correct use of volcanological data may lead to correct explanations of apparently anomalous facts; i.e. the presence of rocks with an apparent 'tholeiitic affinity' in a typical orogenic environment. The geochemical peculiarities of such 'arc tholeiites' (which by the way show  $\tau' < 0.5$ ) have been stressed (JAKES & GILL, 1970; MIYASHIRO, 1973) and their consequent attribution to the earliest phases of the orogenic cycle (JAKES & GILL, 1970) leaves no doubts about their orogenic magmatic affinity.

A further example of the value of volcanological data that contribute and suggest a model for puzzling geodynamic processes, is offered by the recently proposed reconstruction of the interactions at continental plate boundaries in the eastern sector of the Taurus Range (INNOCENTI ET AL., 1976, in press). The Lake Van area (Eastern Turkey) represents a limited sector of the Eurasian continental margin that was continuously compressed during the most recent tectogenic phase, from Oligocene to Pliocene. The northward push of the Arabian continental mass culminated with the local smashing of the Eurasian continent and gave rise to the divergent motion of Anatolian and Iranian microplates, producing marked tensional structures which attained their maximum development in Plio-Quaternary times. Volcanics with a well-defined tholeiitic and Na-alkaline affinity, cover calc-alkaline products of the previous, Miocene, eruptive cycle. This distribution permits a precise chronological definition of the abrupt change in the regional tectonic setting and substantially helps with the reconstruction of the convergence process. The succession of structural events deduced from the relevant variations observed in the magmatic affinity of volcanism in that area, matches the spreading phases that affect the opposite boundary of the Arabian platform (Red Sea-Gulf of Aden tensional system). They thus permit a precise correlation that contributes to a more general analysis of geodynamic processes.

This concise review of examples of the use of volcanological data and their geodynamic implications, stresses the risks of simplistic generalizations that are based on a too fragmentary knowledge of the topic under discussion.

The geological reality, on which our investigations are focussed, is extremely more complex than any proposed model. The evaluation of a single facet of such a reality, in spite of its objective validity, represents however a too partial view to allow significant conclusions.

It is therefore concluded that a substantial contribution can be made by the correct application of volcanological studies,

that provide crucial elements for the solution of the geodynamic puzzle. Such a relevant role can be only attained by avoiding any constraining premise. In this context volcanological data actually contribute to a method of successive approximation, and account for real progress in knowledge.

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