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figg. 9

The importance of exhumed systems in understanding submarine volcanic processes and deposit facies (the example of the Neogene Cabo de Gata volcanic arc, Spain)

L'importanza dei sistemi esumati per la comprensione di processi e depositi vulcanici sottomarini (l'esempio dell'arco vulcanico neogenico di Cabo de Gata, Spagna)

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ABSTRACT - Most of what we know about volcanic seamounts in the Mediterranean region derives from their morphology, a limited number of direct observations, scattered sampling of their surface deposits and geophysical data where available. The understanding of the type of submarine eruptive styles and processes, as well as the associated mass wasting processes, instead largely relies on observations of exhumed volcanic systems, wherein we can study a wealth of different rock types and facies architectures. In this brief contribution we summarize ten years of field studies in the Neogene Cabo de Gata volcanic arc (Spain), which is a very well exposed, large sections of a submerged to emergent cluster of basaltic andesite to rhyolitic stratovolcanoes. Cabo de Gata provides a unique opportunity to understand processes associated with the presently submerged seamounts of the Tyrrhenian region described in this Atlas.

KEY WORD: Mediterranean Sea, Cabo de Gata, volcanic arc, seamounts, subaqueous volcanism, volcanic processes and products.

RIASSUNTO - La maggior parte di ciò che sappiamo dei seamount vulcanici del Mediterraneo deriva da informazioni batimetriche della loro morfologia, da un limitato numero di osservazioni dirette, dove esistenti, da campionamenti puntuali e da dati geofisici. La comprensione dello stile e dei processi eruttivi in ambiente sottomarino, così come i processi legati alle frane e al rimaneggiamento di materiali vulcanici è invece in larghissima misura legata allo studio ed alla comprensione di apparati esumati dove è possibile studiare in dettaglio i diversi tipi di prodotti e la loro architettura di facies. In questo breve contributo sono sintetizzati i risultati principali di oltre dieci anni di studi stratigrafici, di facies e strutturali dell'arco vulcanico miocenico di Cabo de Gata (Spagna), che rappresenta un ampio settore legato alla formazione dell'arco di Gibilterra in cui sono splendidamente esposti interi seamount con prodotti sottomarini effusivi ed esplosivi da basaltico-andesitici a riolitici. La comprensione dei processi vulcanici in ambiente subacqueo nel sistema di Cabo de Gata offre un'opportunità unica per estendere le interpretazioni ai seamount sommersi nel mar Tirreno descritti in questo volume.

PAROLE CHIAVE: Mare Mediterraneo, Cabo de Gata, arco vulcanico, seamounts, vulcanismo subacqueo, processi e prodotti vulcanici.

1. - INTRODUCTION

The physical and chemical properties of water and the interaction of magma with water confer specific characteristics to subaqueous volcanism that distinguish it from subaerial volcanism, in which the surrounding media is air (MCBIRNEY, 1963; KOKELAAR, 1986; CAS, 1992; BATIZA & WHITE, 2000; HEAD & WILSON, 2003; WOHLETZ, 2003; DOWNEY & LENTZ, 2006; ALLEN & MCPHIE, 2009; DEARDORFF *et alii*, 2011; CAS & GIORDANO, 2014). Hence, given similar magma compositions, subaqueous volcanic processes and products are substantially different than their subaerial

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counterparts. A large number of volcanoes on Earth form volcanic arcs, spreading ridges and hot spot volcanoes that have been erupted in submarine conditions. Their study has to be undertaken indirectly by geophysical means (seismic and electromagnetic methods, sonar bathymetries and others), by Remotely Operated Vehicles (ROV) and by dredging that allow direct observation and sampling. At present, for example, our knowledge of the internal structure of the Tyrrhenian volcanic seamounts is largely inferred only based on their morphology reconstructed by bathymetry (Pensa *et alii*, this volume), a limited amount of surface samples and very limited geophysical investigations (e.g. Savelli, 2002; Marani & Gamberi, 2004; Trua *et alii*, 2007).

All these means, however, involve expensive equipment mounted on research cruises that are themselves expensive. Conversely, the exhumation of subaqueous volcanic successions from above sea level provides unique opportunities where to study the processes and products of volcanic seamounts by means of direct and cheap observations.

In order to provide a summary of the main subaqueous volcanic deposits and related emplacement processes that occur in submarine environments, we present in this short contribution a description of the volcanic zone of Cabo de Gata in south-eastern Iberian Peninsula, which is an exhumed part of the Neogene volcanic arc of the Betic-Rif Orogen in the western Mediterranean (Soriano *et alii*, 2012, 2013, 2014). Most of this

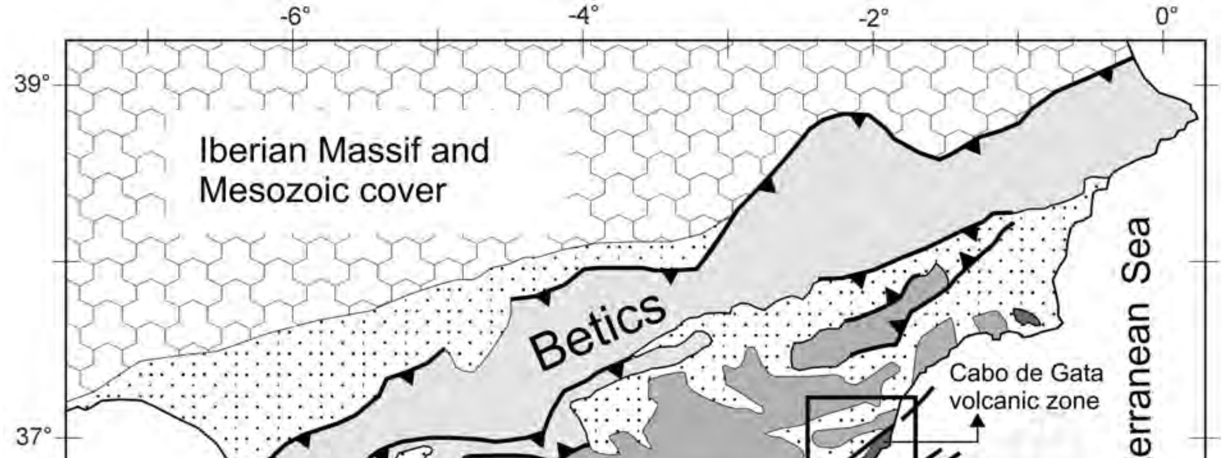

Fig. 1 - Geological map of the Betic-Rif Orogen with location of the Cabo de Gata volcanic zone and of the main volcanic seamounts and ridges forming the magmatic arc of the Betic-Rif.
- *Mappa geologica della catena Betico-Rifana con ubicazione della zona vulcanica di Cabo de Gata e delle principali creste e vulcani sottomarini che formano l'arco magmatico.*

volcanic arc is exposed along volcanic seamounts in the Alboran Sea and only a few portions of it have been exhumed by active wrench tectonics in the Iberian Peninsula and northern Africa (fig. 1). The Betic-Rif is an arcuate orogen formed during Miocene times by the eastward subduction and westward retreat of a subduction slab (FACCENNA *et alii*, 2004; DUGGEN *et alii*, 2004, MATTEI *et alii*, 2014). The volcanic arc of the Betic-Rif is formed by subduction-related calc-alkaline, tholeiitic, shoshonitic and ultrapotassic igneous rocks (CONTICELLI *et alii*, 2009 and references therein). Long-lasting oblique convergence between African and Eurasian plate yielded strike-slip tectonics that was synchronous and post-dated arc magmatism (MATTEI *et alii*, 2014). As a result, the volcanic arc was disrupted into fault-bounded portions with uplifted and downlifted blocks. Cabo de Gata is one of these portions and shows a nearly complete record of submarine to emergent volcanic facies of calc-alkaline composition (SORIANO *et alii*, 2014). Besides, the volcanic facies of Cabo de Gata record effusive and explosive eruptions and the transitional regimes in submarine settings. These features make the volcanic zone of Cabo de Gata a unique natural laboratory where to study the volcanic processes and products of volcanic seamounts worldwide.

The volcano-sedimentary succession of Cabo de Gata is Serravallian to Messinian in age and consists of volcanic rocks interbedded with carbonate and siliciclastic rocks of shallow water environment. Volcanic rocks are dominant toward the lower part of the succession while sedimentary rocks dominate in the upper part. Lavas and volcaniclastic deposits are interbedded throughout the whole area. Here (fig. 2), the eruptive styles and the most significant volcanic facies and remobilized facies of the subaqueous volcanism in Cabo de Gata are characterized.

2. - EFFUSIVE EMPLACEMENT OF LAVAS OF INTERMEDIATE TO FELSIC COMPOSITIONS

When lavas extrude non-explosively in subaqueous environments, the very fast rate of cooling due to the large heat capacity of water

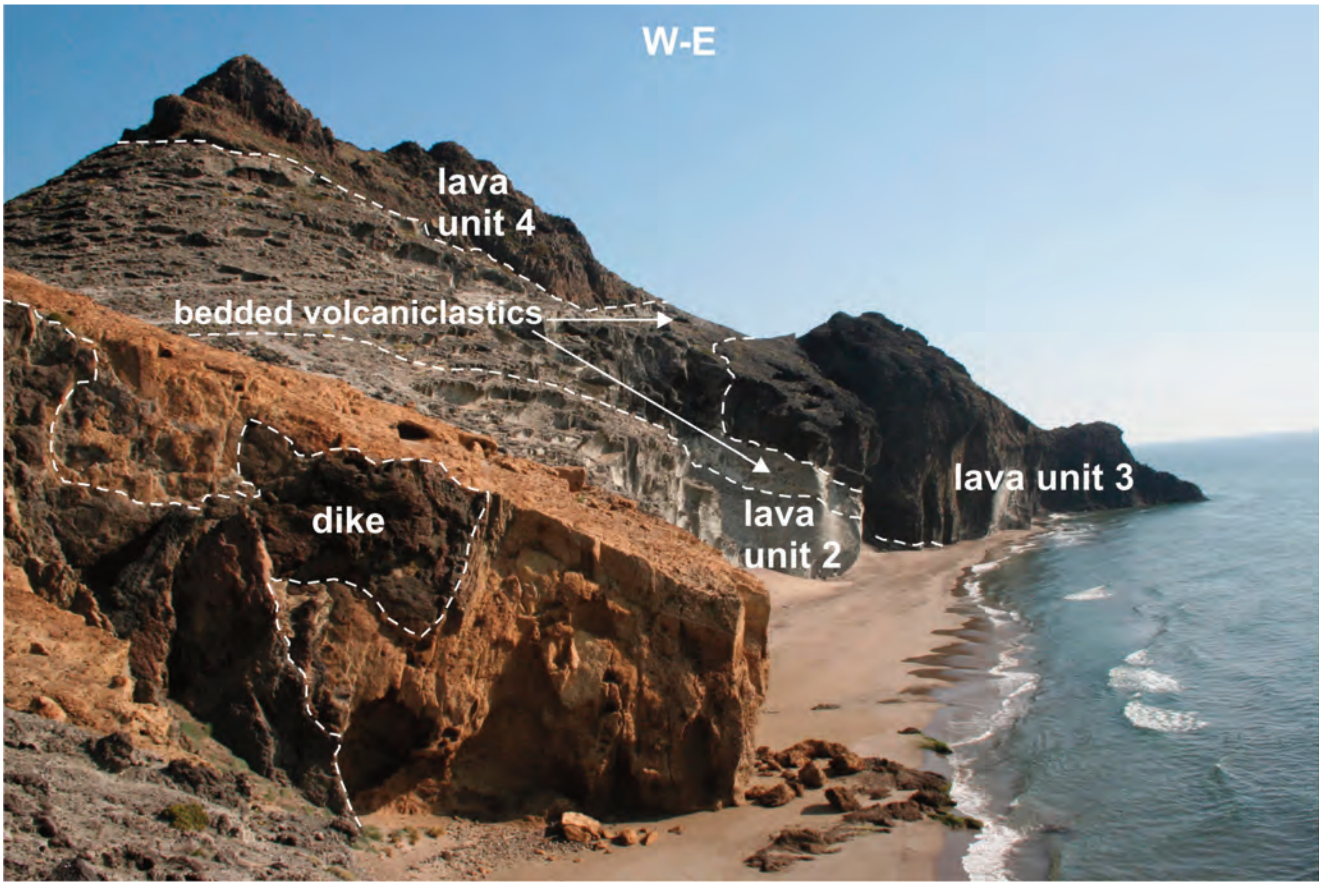

Fig. 2 - Stratigraphic succession of Cabo de Gata at Playa del Barronal. Lava units are formed by andesite coherent facies and hyaloclastite breccias and are interbedded with andesite volcaniclastic rocks.
- *Successione stratigrafica di Cabo de Gata a Playa del Barronal. Le unità laviche sono formate da facies coerenti di andesite e brecce ialoclastiche intercalate a vulcanoclastiti andesitiche.*

induces the very fast crossing of the glass transition temperature and the subsequent thermal contraction is accommodated by brittle fracturing known as quench fragmentation. The results of quench fragmentation are glassy subequant and angular clasts with curviplanar edges known as hyaloclastite (WATTON *et alii*, 2013; VAN OTTERLOO *et alii*, 2015). Quench fragmentation and hyaloclastite occur at the contacts of hot magma and ice or water. Where quench fragmentation occurs due to the interaction with water-saturated sediments, the resulting lithofacies is a mix of hyaloclastic fragments and fluidized sediment, making a rock type known as peperite (SKILLING *et alii*, 2002). Hence, hyaloclastite and peperite are also common lithofacies at the contacts between shallow-level subvolcanic bodies, such as sills and dikes, and the host rock.

The composition of lavas in Cabo de Gata range from basaltic andesite to rhyolite and they form tabular bodies and domes (SORIANO *et alii*, 2014). The overall facies architecture of lavas consists of an outer carapace of hyaloclastite breccia grading into coherent facies with columnar jointing toward the interior of the lava body (SORIANO *et alii*, 2013). Hyaloclastite typically shows a jigsaw-fit texture in which hyaloclasts fit together (fig. 3A and 3B). However, due to the growth dynamics of lava flows and domes, hyaloclasts may individually rotate and the jigsaw-fit texture appears to be locally disorganized. As a result, jigsaw-fit hyaloclastite grades into clast-rotated hyaloclastite in the external carapace of lavas (cf. SCUTTER *et alii*, 1998). The hyaloclastite carapace is usually more vesicular than the internal part of the lava body and shows crude flow banding subparallel to the margins. These features have been observed in subaerial lavas too, but in submarine lavas banding consists of an alternation of vesicular bands and non-vesicular bands in which dense hyaloclasts have a jigsaw-fit texture (fig. 3C).

The thickness of the hyaloclastic carapace can reach tens of metres and more and show pervasive fragmentation with domains that are silt-sized grading either transitionally or abruptly into coarser grained domains, up to block-sized. The main process that allows quench fragmentation to be delayed after magma effusion, which allows the lava to flow before being transformed into hyaloclastite is the development of an insulating vapour film all around its surface (CAS & GIORDANO, 2014 and references therein). The vapour film is stable for as long as the transfer of thermal energy from the lava to seawater is able to keep the vapour pressure equal or above the hydrostatic pressure of the overlying column of seawater. As lava progressively cools, eventually the film collapses and liquid water enters in contact directly with the lava inducing quench fragmentation. The collapse of the vapor film may also be triggered dynamically while the irregular and blocky upper surface of the lava is moving. The access of liquid water to the interior of the typically viscous arc lavas is greatly helped by fractures that are usually present also in subaerial domes. This may justify the common irregular distribution of

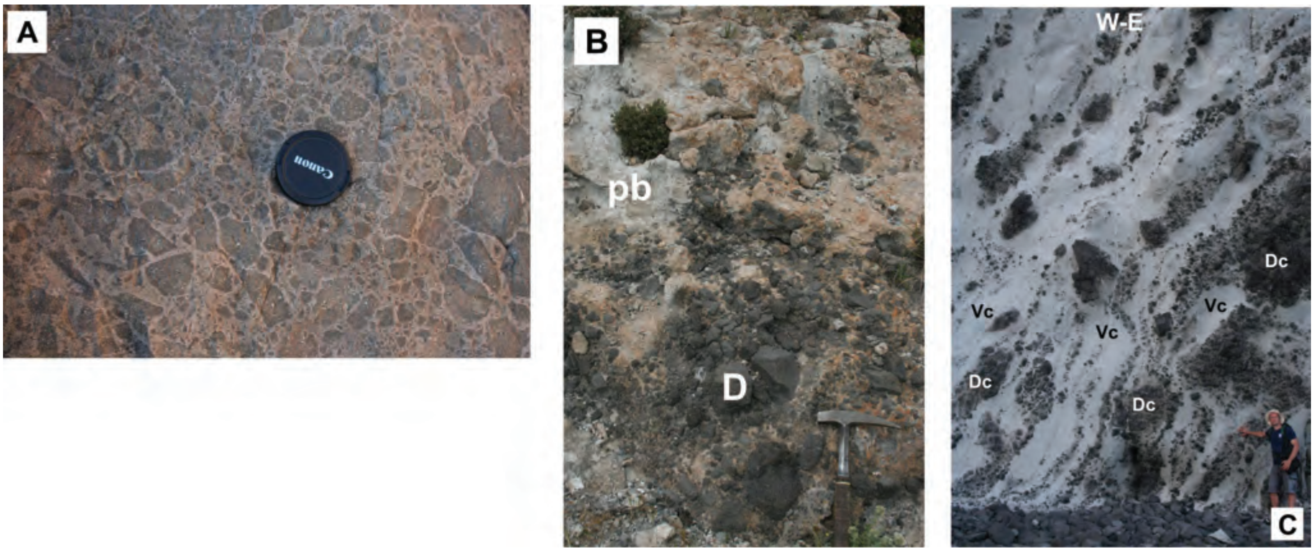

Fig. 3 - A: Jigsaw-fit hyaloclastite in the external carapace of andesite lavas. B: Apophysis of a dacitic dike (D) intruding dacite pumice breccia (pb). Dike shows a diffuse contact with pumice breccia consisting of dense hyaloclasts with jigsaw-fit texture in a matrix of pumice breccia. C: Flow banding in the external carapace of andesite lavas. Banding is formed of bands with vesicular clasts (Vc) and bands with dense clasts and jigsaw-fit texture (Dc)
- *A: Ialoclastite con tessitura a jigsaw nel carapace esterno delle lave andesitiche. B: Apofisi di un dicco dacitico (*D*) che si intrude in una breccia pomicea dacitica (*pb*). Il dicco presenta un contatto sfumato con la breccia di pomici costituita da ialoclasti densi in tessitura a jigsaw all'interno di una breccia pomicea. C: Bande di flusso nel carapace esterno delle lave andesitiche. La bandatura è formata da fasce con clasti vescicolati (*Vc*) e fasce con clasti densi e tessitura a jigsaw (*Dc*).*

hyaloclastite facies and grainsizes as pre-existing fractures and other weakness domains, for example vesicular flow banding domains (fig. 3C), allow in some regions the deep percolation of water throughout the whole lava body. In addition, quench fragmentation (or granulation) of the lava can occur at temperatures much lower than the glass transition temperature, explaining the development of thick hyaloclastic carapace by the percolation of water through the cooling but still hot lava body well after its stop (Porreca *et alii*, 2014).

A significant consequence of the development of thick, water-saturated hyaloclastic carapaces, tens to hundreds of meters thick, is that incoming lava from prolonged dome effusions can be accommodated by intrusion through such carapace (e.g. Ponza island; De Rita *et alii*, 2001). In such mechanically weak environments, dykes can expand laterally forming large coherent lava domains tabular to wavy in shape, up to tens of metres thick, with or without sharp vitreous margins grading into coarse hyaloclastite that intrudes the hosting hyaloclastite (fig. 4A). Columnar joining is well developed and generally rather irregular. In some cases the lava flows laterally and may spread into cryptodomes hosted by the hyaloclastite carapace (fig. 4B)(Aubourg *et alii*, 2002; Porreca *et alii*, 2015).

Fig. 4 - A: Dyke intruded in fine grained layered hyaloclastite (Ponza island, Italy); B: Cryptodome fed by a vertical dyke emplaced in layered hyaloclastite (Ponza island, Italy).

- A: Dicco intruso in una ialoclastite stratificata a grana fine (isola di Ponza, Italia); B: Criptodomo alimentato da un dicco verticale messo in posto all'interno di una ialoclastite stratificata (isola di Ponza, Italia).

Fig. 5 - Shear band in hyaloclastite accommodating deformation and fluid escape.
- Shear band *in ialoclastite che accomodano la deformazione e la fuoriuscita dei fluidi.*

The volumetric changes due to such intrusions result in the development of shear bands and fluid escape through the hyaloclastic carapace (fig. 5) (De Rita *et alii*, 2001).

3. - EXPLOSIVE ERUPTIONS

The products of explosive eruptions in Cabo de Gata are globally less voluminous than lavas emplaced during effusive eruptions. This is a common feature in submarine environments as the hydrostatic pressure provides an additional confining pressure to magmatic volatile expansion needed for magmatic explosivity. As a general rule, the deeper is the submarine environment the lesser will be the explosivity of magmas even for evolved compositions. Based on considerations on the critical point for water, explosivity is virtually suppressed at depths >3000 m (Cas & Giordano 2014, and references therein). Furthermore, the dynamics of the eruptions plumes would be greatly affected by the water environment into which they develop as compared to their subaerial counterparts (Cas & Giordano 2014, and references therein).

In addition, the settling behaviour of vesicular clasts in water is totally different from that in air. Pumice clasts may even float for prolonged times before becoming water logged and sink to the seafloor (Cashman & Fiske, 1991; Allen & McPhie, 2000; Allen *et alii*, 2008). Pumice rafts have been observed for example in the Pacific formed by floating pumice of submarine explosive eruptions. This also means that pumice can be transported for large distances and sink in deep environments explaining some unexpected findings of explosive products embedded in deep-sea sediments (Bryan *et alii*, 2012).

Explosive activity may therefore become more frequent as seamounts grow close to the sea surface to become emergent. In this conditions explosivity may be increased by explosive interaction with water (phreato-magmatism) which originates the typical surtseyan style, characterised by intermittent jets of fragmented magma and base surges (Kokelaar, 1986; Cas *et alii*, 1989; Brand & Clarke, 2009). Reference descriptions of such style are those of Surtsey (Iceland) in 1952, Capelinhos (Azores) in 1963 (White & Houghton, 2000 and references therein). The transition from dominantly effusive to dominantly explosive volcanism in emergent sequences is well described also in ancient successions (e.g. Cas *et alii*, 1989).

At Cabo de Gata, individual volcaniclastic units are relatively small-volume deposits corresponding to

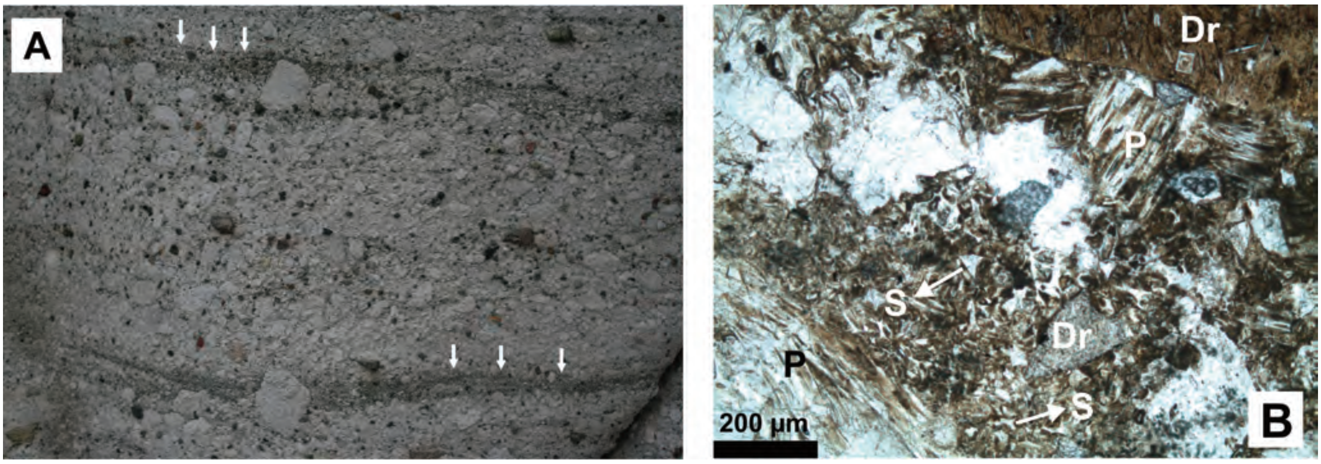

Fig. 6- A: Dacite bedded pumice-rich breccia with bedding planes marked by crystal and lithic-rich horizons (arrows). B: Plane-polarized light photomicrograph of pumice-rich deposits with tube pumice clasts (P), bubble-wall and cuspate glass shards (S) and lithics of dense angular clasts (Dr).
- *A: Breccia dacitica, bandata, ricca in pomici con livelli marcati da orizzonti ricchi in cristalli e litici (frecce). B: Microfotografia a nicol paralleli di depositi ricchi in pomice con clasti di pomice tubolare (P), shard vetrose a forma di cuspide e di pareti di vescicolazione (S) e clasti litici densi angolari (Dr).*

magmatic to surtseyan explosions of emergent basaltic andesite lava flows to rhyolitic domes. The related volcaniclastic deposits are interbedded with lavas and the main facies types are pumice to lithic-rich breccia, crystal-rich tuff and fine tuff. All of them show variable amounts of juveniles and lithics attributed to the explosive fragmentation of magma and, occasionally, to magma-water interaction processes (fig. 6). In Cabo de Gata, pyroclastic rocks do not show evidences of hot emplacement structures, such as degassing pipes, welding and columnar jointing; they are typically clast-supported and lack fine ash matrix. These features suggest gravitational settling through water and subsequent remobilization by cold granular flows with grain-to-grain support mechanism, although tractional structures observed in the finer facies may suggest water-support mechanisms in dilute flows (e.g. turbidites).

4. - VOLCANO INSTABILITY AND MASS WASTING PROCESSES

Instability of volcanic edifices may trigger lateral collapse of volcanoes and deposition of volcanic debris avalanches in submarine settings. Sector collapse may involve ocean islands volcanoes like Hawaii and the Canary Islands yielding large-scale events that accumulate volcanic debris on the sea floor (McGuire, 1996 and references therein), subaerial stratovolcanoes like Mount St. Helens, Mount Shasta and Colima, and volcanic domes like Unzen, Montserrat, Mount St. Augustine and Cerro Pizarro yielding small-scale events (McGuire, 1996 and references therein). Volcanic seamounts are prone to collapse laterally and to trigger debris avalanche that accumulate on the sea floor too. Actually, the water saturated environment, the large presence of hyaloclastic debris and the almost ubiquitous presence of diffuse hydrothermal alteration make seamount particularly prone to collapse events. The processes and products of volcanic debris avalanches have been studied in situ on subaerial deposits and with geophysical methods on submarine Holocene examples (e.g. Chiocci & De Alteriis, 2006). Occurrence of submarine ancient deposits that might allow for in situ studies is rare in the geological record. For this reason, the propagation mechanisms of volcanic debris avalanches in a subaqueous media still remains poorly understood. Submarine volcanic debris avalanches of Cabo de Gata are massive and show the characteristic "mixed facies" that typifies subaerial volcanic debris avalanches too. "Mixed facies" consists of megablocks of up to 10^4 cubic meters "floating" in a matrix of smaller angular clasts with the same composition than the blocks (Soriano *et alii*, 2012) (fig. 7). Some blocks are pseudopillows with radial jointing, many of them are shattered, and at the basal contact with the matrix many blocks exhibit anastomosed shear planes and cleavage. In Cabo de Gata, volcanic debris avalanches are monomictic low-volume deposits with small aerial distribution and short run out distances. These features agree with deposition from the sector collapse of lava flow and dome complexes, with megablocks corresponding to the internal and coherent parts of lavas while matrix corresponds to the external hyaloclastite carapace.

5. - CYCLIC AND EMERGENT VOLCANISM

The depositional setting of volcanic rocks of Cabo de Gata was dominantly submarine. However, a number of evidences suggest that the emergent portions of volcanic seamount may have been involved in the eruption dynamics of Cabo de Gata

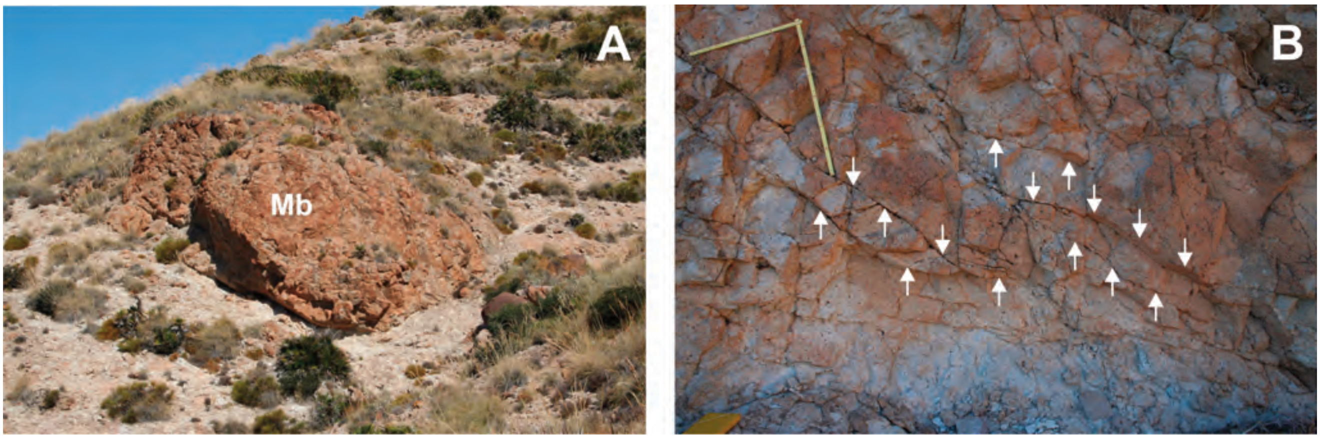

Fig. 7 - A: Dacite megablock with a basal sharp contact in a matrix of clasts of the same composition than the block. B: Detail of the sigmoid shear planes (arrows) at the basal contact of a megablock.
- *A: Megablocco di dacite con un contatto basale netto in una matrice di clasti di medesima composizione. B: Dettaglio dei piani di taglio sigmoidali (frecce) al contatto basale di un megablocco.*

volcanism. For example, some pumice-rich breccia deposits contain well-rounded reddish pebbles that are attributed to sources above wave base with oxidizing conditions; some debris avalanche deposits contain irregular domains with diffuse margins that consists of well-rounded cobbles occasionally supported in a sandy matrix (fig 8A); in the central part of Cabo de Gata, a rhyolite pumice breccia is conformably overlain by siltstone beds with accretionary lapilli with the same mineralogical composition than the pumice breccia (fig. 8B). Well-rounded reddish and sandy matrix clasts suggest reworking in an oxidizing highly energetic depositional environment, likely a beach. These clasts were subsequently mixed together with juvenile particles during explosive eruptions and were deposited in deeper settings by granular flows or were transported by debris avalanches that affected the emergent part of volcanic seamounts. Accretionary lapilli indicates subaerial conditions and could have been formed either by submarine-vented explosions that crossed the water-air interface or by subaerially vented explosions.

Interbedding of volcanic and sedimentary rocks in the volcano-sedimentary succession of Cabo de Gata allows characterizing volcanism as cyclic. During eruptive periods, volcanic edifices were constructed and partly dismantled by mass wasting processes. During non-eruptive periods, carbonate and siliciclastic deposition, erosion of volcanic edifices and remobilization of volcanic deposits took place. Eruptive periods were dominantly effusive, though minor explosive eruptions occurred, and non-eruptive periods were longer in time though the accumulate thickness was much less than in eruptive cycles (fig. 9).

The cyclicity of emergent volcanism is affected by the interplay between:

- growth and waste of the volcanic pile
- tectonic uplift and/or subsidence
- volcano-tectonic uplift and/or subsidence
- variations of the sea level

6. - CONCLUSIONS

Even though we do not have access to the interior of the volcanic seamounts we can use the analogue of exhumed submarine volcanic systems to infer the main eruption styles and processes associated with their growth. The main constraining factors to be taken into account are the physical properties of water and particularly the pressure, the density and the heat capacity. In a very simplified scheme we may expect effusive volcanism at depths >1000 m. In consideration of the chemistry and volatile content of magmas, the potential for explosive activity increases as the overlying water table progressively shallows. The dominant rock types are hyaloclastite (either in situ jig-saw fit or resedimented clast rotated) and coherent lavas. Explosive deposits may become important in emergent volcanism where also magma water interaction can enhance explosivity. Catastrophic sector collapses may potentially occur as seamounts grow along the steeper slopes and especially in emergent volcanism. This relatively simple scheme is validated by observations of exhumed seamounts, such as at Cabo de Gata, and allows to extend the interpretation of the present day morphology, stratigraphy and structure of submerged seamounts.

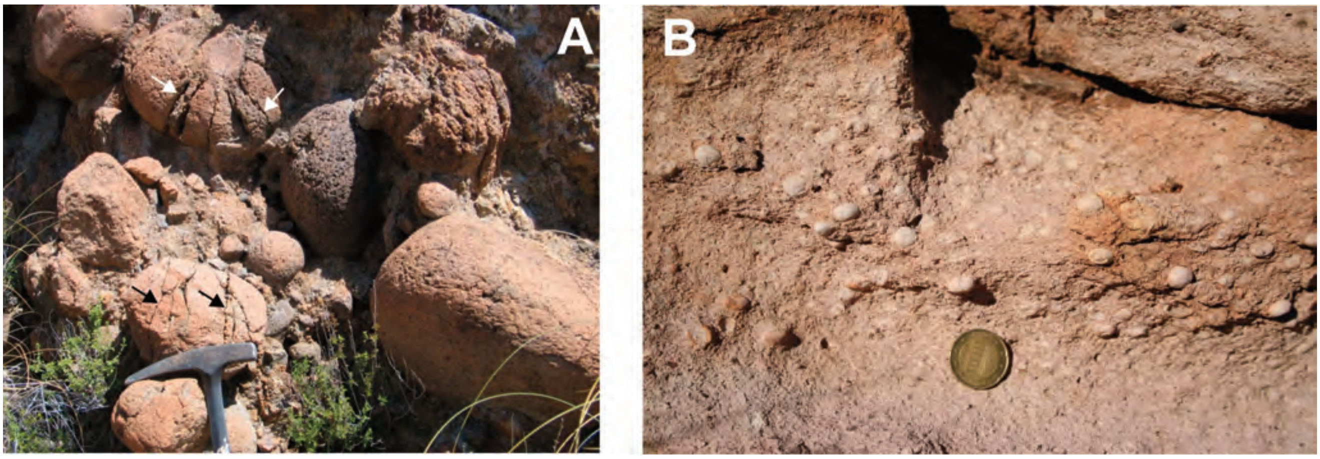

Fig. 8 - A: Cobble domain in the lowermost part of a debris avalanche deposit with fractures in shattered cobbles (arrows). B: Reddish siltstone bed with accretionary lapilli of rhyolitic composition.
- A: Presenza dominante di ciottoli nella parte più bassa di un deposito di debris avalanche con fratture in ciottoli frantumati (frecce). B: Letto di siltite rossastra con lapilli accrezionari di composizione riolitica.

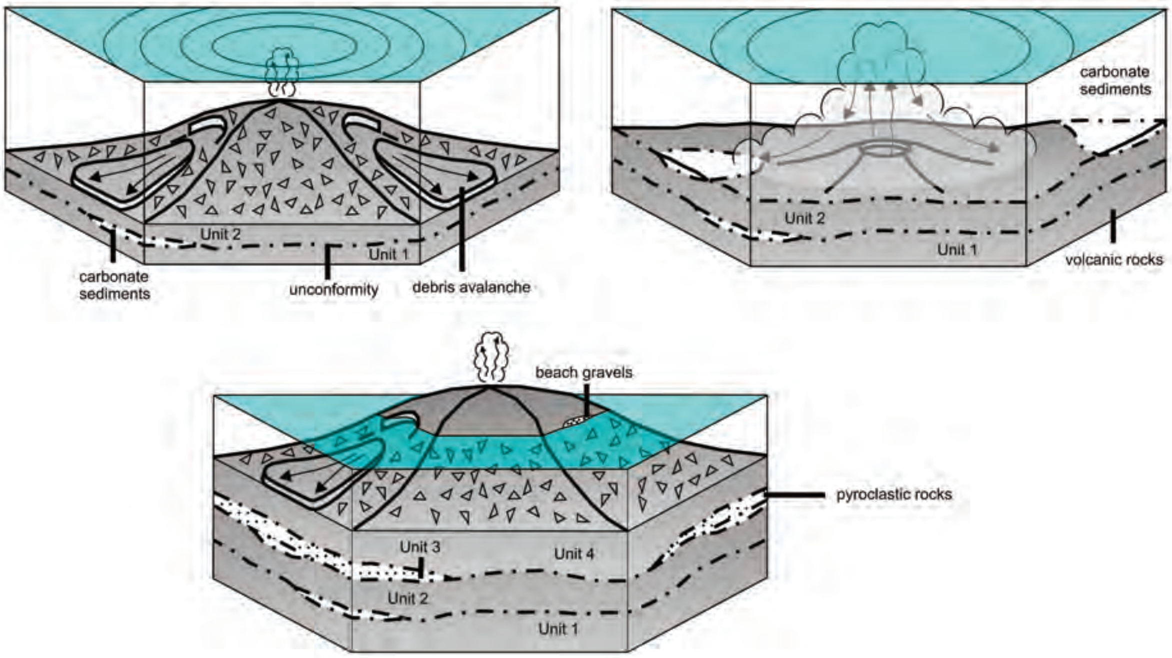

Fig. 9 - Schematic reconstruction not to scale of the cyclic and emergent volcanism in Cabo de Gata. The volcanic dome shown may have formed part of a larger dome complex.
- *Ricostruzione schematica non in scala del vulcanismo ciclico ed emergente a Cabo de Gata. Il domo vulcanico rappresentato potrebbe essere parte di un complesso di domi più grande.*

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