Geologie en Mijnbouw **72**: 363–373, 1994.

Coeval genesis of pillow lava on the sea floor and under a thin cover of unlithified sediments (and associated formation of peperites)

A. Assorgia[1] & D. Gimeno[2]
[1] *Dipartimento di Scienze della Terra, Università di Cagliari, Viale Trentino 51, Cagliari 09100, Italy;* [2] *Departament de Geoquímica, Petrologia i Prospecció Geològica, Universitat de Barcelona, 08071 - Barcelona, Spain*

Received 4 February 1993; accepted in revised form 30 October 1993

Key words: subaqueous pillow, intrusive pillow, peperitic lithofacies, Miocene, Sardinia, Western Mediterranean

Abstract

The Guardia Marina beach (Sardinia island, Western Mediterranean, Italy) contains outcrops of subalkaline basaltic pillow lava within a Miocene sedimentary sequence of shallow marine facies. The northern sector of the beach is characterized by the presence of feeder dikes terminating at their upper ends in antigravitative toothpaste-like massive pillows and lateral expansions of highly vesiculated and cupola-like hollow pillows. The central sector of the beach shows partially eroded pillows and pillowed dikes, as well as sandwiched layers of sediments between laterally expanded pillows. The southern sector of the beach contains well-developed pillows (intrusive with respect to the sedimentary sequence) with a clear development of peperitic lithofacies at the magma–sediment interface.

The lateral continuity of the sedimentary beds suggests a coeval growth of pillows at the magma–water and magma–sediment interfaces, as well as a recurrent process of pillow-growth from feeder dikes. The multiple-rind structure in the pillows in the southern sector of the beach confirms the very shallow marine environment inferred from fossil fauna and sedimentary lithofacies. The early erosion of the pillows in the central and northern sector of the beach accounts for the proximal character of crystal-rich epiclastic layers within the calcarenitic sequence.

The Guardia Marina outcrops show that pillow lava can correspond both to a subaqueous environment and to a growth of pillows under a thin layer of poorly lithified sediments. The generally accepted concept that pillow lava indicates a subaqueous environment must therefore be tested through an accurate study of the pillow–sediment interface.

Introduction

There are numerous descriptions of pillow lava lithofacies in the literature. These products of magma–water interaction are well known, but in the last 20 years knowledge of the genesis and significance of their internal and external structures, as well as of the lithofacies associated with the pillows, has greatly improved.

From a morphological point of view, some pillows are in fact isolated sacks of magma, but most of them are tube-like bodies which are interlaced and rooted in a larger pillow or emerge directly from the upper part of a feeder dike. Papers by several authors (Moore 1975; Yamagishi 1985, 1991; and references therein) have furnished detailed descriptions of the external features and internal structures of pillows, as well as general characteristics of the association of lithofacies and petrography of pillows and pillow-derived hyaloclastics.

Peperites and peperitic facies, on the other hand, are not so well known. Nevertheless, some papers have provided most of the basic tools for the study of this magma–wet sediment interaction lithofacies. Kokelaar (1982) describes several examples of the genesis of peperites in the margins of shallow emplaced sills showing some of the physical constraints to peperite formation. Busby-Spera & White (1987) discuss the different types of peperitic lithofacies generated in different host sediments. Kano (1989) gives a thorough description of the place of development of peperitic lithofacies in a volcaniclastic shallow marine sequence

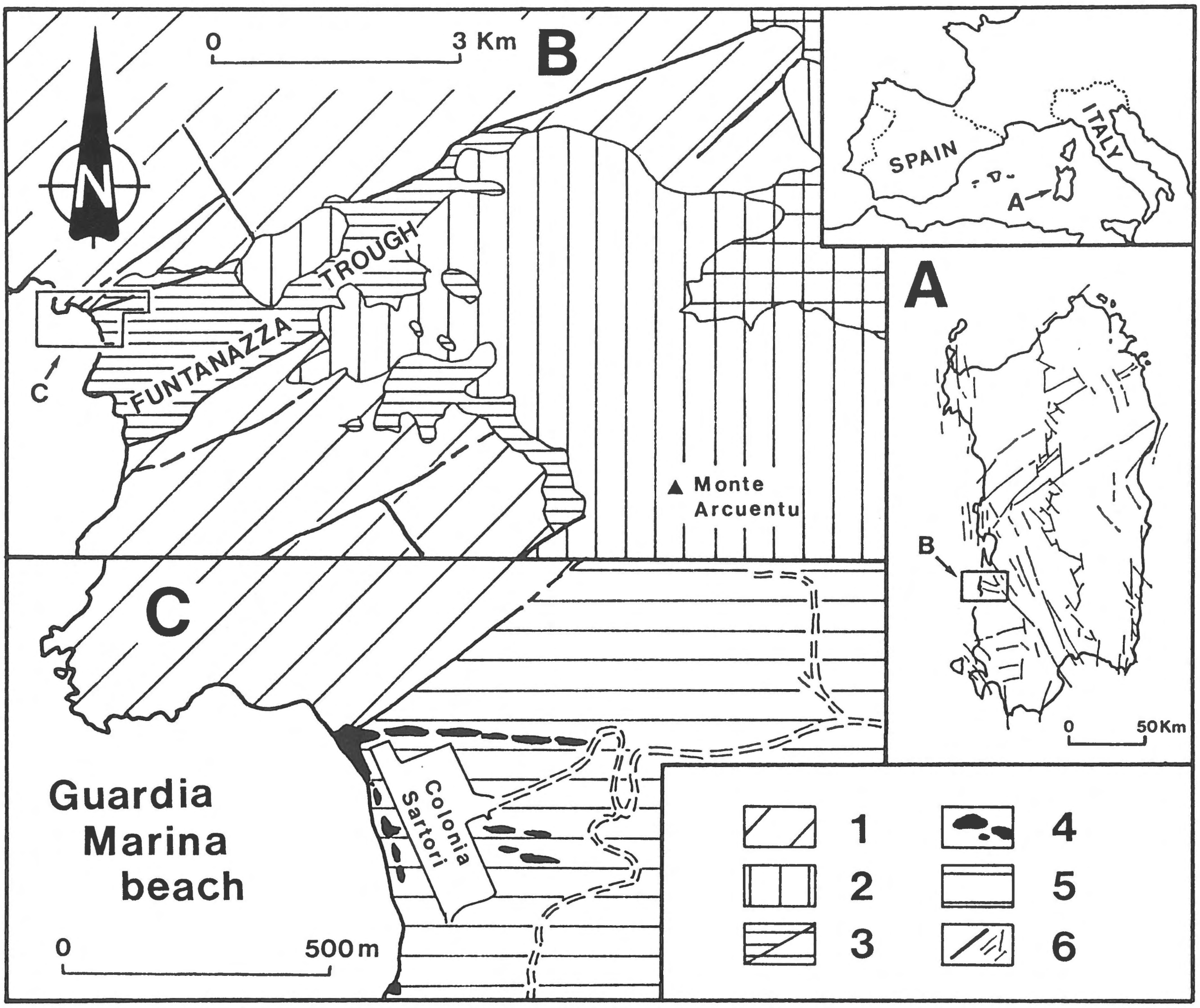

Fig. 1. Geological sketch of the Guardia Marina beach. Legend: 1. Pre-Oligocene rocks. 2. Basaltic rocks of the Arcuentu volcanic complex (s.l.). 3. Miocene sedimentary rocks of the Funtanazza trough, including pyroclastic flows and epiclastic layers. 4. Basaltic dikes and pillows of Guardia Marina beach. 5. Quaternary rocks of the Sardic Trough. 6. Faults. A. Caenozoic structural framework of Sardinia island (after Cherchi & Montadert, 1982, modified).

containing subaqueous lava flows, hyaloclastites, pillows, etc.

Conventionally, the genesis of pillow lavas is interpreted as taking place at the magma–water or magma–ice interface. Nevertheless, we can cite a number of references of pillows that developed under a thin pile of sediments (e.g. Snyder & Fraser 1963). Recently, Kano (1991) has described a clear example of pillowed sills from the Miocene of Japan.

The present paper reports on an exceptional site of the Miocene on the island of Sardinia (Fig. 1) where, within a small area on a beach and in the surrounding cliffs, a large number of the aforementioned lithofacies can be recognized: magma–water interaction from feeder dikes, typical pillow lithofacies (massive and scoriaceous cores, glassy skins, concentric magmatic flow inside a pillow, etc.), and pillow growths under a thin blanket of unconsolidated sediments (from a few centimeters to some meters in thickness), with typical pillow features including multiple rinds (related to implosion of pillow) and peperitic lithofacies in the margins of the pillows.

Geological setting

Sardinia has a well-exposed Cenozoic volcanism, mainly developed along an Oligo-Miocene rift system that crosses the island from NNW to SSE (Sardic Trough, Cherchi & Montadert 1982). This volcanism is mainly of calc-alkalic type (calc-alkalic s.l. volcanic cycle, Beccaluva et al. 1989). There appears to be general agreement that it developed within a geodynamic framework with an active margin, which implies subduction of an oceanic microplate located ESE of Sardinia and dipping towards the present north-northwest (Coulon 1977, Savelli et al. 1979, Beccaluva et al. 1989, etc.).

Published K/Ar geochronological data of the calc-alkalic s.l. cycle suggest a time span ranging from 32 Ma to 11 Ma for the whole succession. These data show that volcanism occurred before, during and after the thinning of the margin of the European continental crust that led to the drift and counter-clockwise rotation of the Sardinia-Corsica microplate and subsequent creation of the Provençal-Nord Balearic oceanic basin in the northwestern Mediterranean during the Aquitanian-Early Burdigalian.

The Guardia Marina pillow outcrops are located in the Funtanazza trough, an ENE-WSW tectonic graben on the western coast of Sardinia (Fig. 1). This graben is interpreted as a minor structure associated with the main Oligo-Miocene rift system, in the same way as other E-W tectonic structures (Cixerri and Narcao grabens).

The Funtanazza graben is connected with the Sardic Trough by the Arcuentu calc-alkalic volcanic complex (30–16 Ma, Lonis 1983, Assorgia et al. 1985). The complex, covering some 100 km^2, represents an episode of volcanism beginning with an initial stage of subaerial activity (domes and lava flows of basalt and basaltic andesite), followed by a subaqueous stage (starting with some rhyolitic pyroclastic flows and mainly characterized by a large volume of andesitic and basalt-andesitic pillow-breccia, hyaloclastites and fossiliferous epiclastites), and ending with thick subaerial basaltic flows.

The Funtanazza graben is located between Arcuentu and the Mediterranean sea (sheet 225 IV NO of the Carta Geologica d'Italia). It has a rectangular ENE-WNW morphology and covers an area of 4 × 2 km. Its sedimentary fill (Gimeno & Onnis 1986, Assorgia et al. 1988) is composed of epiclastic and sedimentary rocks, deposited in a shallow marine sequence with ash and lapilli-tuffs, *Lithothamnium* limestones and medium to coarse-grained calcarenites, epiclastic sandstones and matrix-supported rudites with porphyritic olivine-augite basaltic clasts. All these rocks contain abundant remnants of *Chlamys*, *Pecten*, echinoids, corals, etc. The top of the outcropping sequence immediately to the south of the Guardia Marina beach corresponds to the Burdigalian (Assorgia et al. 1991), so the studied rocks might be Burdigalian or more recent.

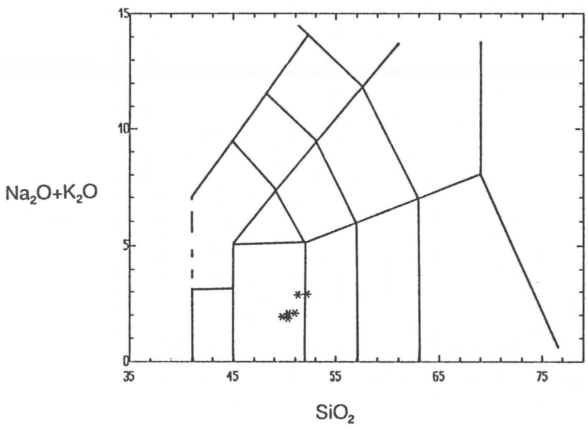

Fig. 2. Total Alkali versus Silica (TAS) diagram showing major-element composition of basaltic dikes and pillows of Guardia Marina beach (cf. Le Maitre et al. 1989). Percentages as in Table 1, normalized to 100 %.

Several types of volcanic products occur interlayered with sedimentary rocks. We can distinguish acid pyroclastic flows, basaltic dikes, and pillow lavas. The latter crop out on the beach and in the small cliffs in the proximity of the old Colonia Sartori buildings. We studied the outcrops on the beach and in the walls of the cliffs, as well as the subaqueous outcrops of dikes and pillows down to the −3 m level.

Petrography and geochemistry of pillow lavas

The comparative study of the pillows and dikes shows several stages in the crystallization history of the magma. Fresh samples of pillow rims are characterized by a prevalence of brown glass. The presence of phenocrysts is restricted to olivine, radially aggregated glomerules of plagioclase phenocrysts, and large twinned augitic clinopyroxene phenocrysts. A second generation of acicular microlites of plagioclase is also present. The entire paragenesis shows a distinctive idiomorphic character.

Table 1. Chemical analysis of Guardia Marina beach basaltic rocks. Major elements and Loss on Ignition (LOI) expressed in weight percentages; Nb, Zr and Y expressed in ppm. Samples fn22 and fn21 correspond to two holocrystalline dikes; fnbd, fnid, fcd1 and fcd2 correspond to a seriate sampling from outer (porphyritic hypocrystalline) to inner (holocrystalline) zone of the upper sector of a dike near to the level of growth of pillows.

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO
fn22	49.97	0.56	13.32	9.42	0.17	10.41	9.47
fn21	50.59	0.58	13.67	9.52	0.17	10.35	9.33
fcd2	49.67	0.47	12.87	9.68	0.15	10.96	10.71
fnid	50.32	0.54	13.27	9.75	0.16	9.83	10.44
fnbd	49.82	0.55	13.50	9.80	0.13	10.36	10.17
fcd1	49.46	0.50	12.77	9.64	0.16	10.89	10.43

Sample	Na_2O	K_2O	P_2O_5	LOI	Nb	Zr	Y
fn22	1.97	0.78	0.08	0.54	5	64	16
fn21	2.02	0.78	0.08	1.70	6	65	15
fcd2	1.73	0.12	0.06	1.60	4	41	13
fnid	1.79	0.18	0.05	1.45	4	47	13
fnbd	1.85	0.12	0.06	1.88	4	48	13
fcd1	1.73	0.09	0.05	1.60	4	44	11

The tops of feeder dikes and the cores of massive or poorly vesiculated fresh pillows are texturally similar to the rims of the pillows. Large numbers of plagioclase skeletal microlites are present, so the texture can be denoted as porphyritic-intersertal. Locally, the phenocrysts are smaller in size than those in the pillow rim, but no traces of important corrosion have been detected.

The dikes are characterized by a substantially smaller proportion of glass, hence very few intersertal spaces exist. Olivine phenocrysts are small and subidiomorphic or rounded. The clinopyroxene has undergone intense corrosion and embayment. Some plagioclase glomerules are rounded due to resorption. The texture is porphyritic and mesocrystalline.

Six selected samples of dikes and pillows were analyzed (Table 1) and classified. All the samples are plotted within the subalkaline basalts field in the TAS diagram (Le Bas et al. 1986; Le Maître et al. 1989; Fig. 2), as well as in the more complex diagram proposed by Cox et al. (1979). Minor and trace element discrimination diagrams (Pearce & Cann 1973; Mullen 1983; etc.) show that these basaltic rocks plot at the border between the island-arc tholeiitic basalt field and the calc-alkalic basalt field.

Pillow lithofacies

The upper levels cropping out at the cliffs consist of conglomeratic sandstones that overlie with an erosional unconformity a layer of calcarenitic sandstone which is a few meters thick. Pebbles and cobbles consist of massive porphyritic basalt and show subrounded to subangular morphology. The basalt is fresh and contains large olivine (0.2–0.8 mm) and clinopyroxene phenocrysts.

The calcarenitic sandstone contains synsedimentary faults (vertical displacement of centimeters to decimeters), that are fossilized by the aforementioned conglomeratic sandstones. The calcarenitic beds consist mainly of sand-size algal fragments, aggregated by a thin rim of calcitic cement. Remnants of bryozoa, foraminifera and other skeletal fragments are randomly distributed through the sediment. In some strata there are large quantities of phenocryst fragments of olivine, clinopyroxene, plagioclase and opaque minerals, local-

Fig. 3. Top of a dike structure, with transition from vertical to horizontal flow-banded lithofacies at the growth level of toothpaste-like pillows. Exposed dike is 2 meters high. Northern sector of Guardia Marina beach.

ly concentrated in placer-like deposits of millimeter to centimeter thickness. Pillow and feeder dikes occur in the lower section on the beach.

There is a prevalence of pillow lava over feeder dikes at the Guardia Marina beach. The feeder dikes have an E-W direction and can be mapped with some discontinuity over a distance of a kilometer on land (Zuffardi et al. 1956). They continue onto the sea floor where they crop out between the present beach sands. The pillow lithofacies are substantially different in the northern and southern sector of the beach. The northern sector is characterized by the presence of the upper parts of feeder dikes that end in pillow expansions.

The dikes show magmatic banding (enhanced by the accumulation of phenocrysts) parallel to the vertical walls of the igneous body, as well as a gradual transition to the horizontal disposition of bands at several places where pillow growth begins (Fig. 3). The transverse sections of pillows also show parallel concentric bands (Fig. 4).

Pillows are either massive (as in the case of the main dike that continues into the sea) with antigravitative development, or they show lateral expansion with vesiculation to a greater or lesser extent. Packed pillows produced by lateral expansion from a dike show a deformed lower surface (winged brachiopod-type transversal section at several places), suggesting a ductile accommodation to an undulate substratum formed by the top of previously generated pillows.

Some pillows show a highly vesiculated core with vesicles filled by calcite. In other cases the upper half of the pillow core is hollow, while the upper skin can be a few decimeters thick (cupola-like hollow pillow). The floor of the hollow is flat and irregular, without clear traces of stalagmite-like droplets of lava.

The relationship between the pillows of the northern sector and the calcarenitic sediments is quite clear: the upper parts of the dikes are eroded and covered by calcarenites at the level where the pillows developed. Some non-eroded pillows contain partially recrystallized valves of pectinids, mainly arranged as a rim on the pillow.

The southern sector of the beach is characterized by the presence of palagonitized lapilli-sized

Fig. 4. Close-up of concentric flows at the budding sector of a pillow. Top part of a vertically banded dike. Note hammer for scale. Northern sector of Guardia Marina beach.

tuffs, interbedded with calcarenites, centimeter-thick basalt layers which scarcely show a lateral continuity over some meters, isolated decimeter-sized pillow-like basaltic bodies, etc. Some of the vertical dikes with a thickness of meters (and clearly intrusive with respect to the calcarenitic layers) are cross-cut and eroded at the contact with the upper conglomeratic sandstones.

The central zone of the beach displays a transversal section of well-developed, meter-sized pillows. The rock consists of porphyritic vesicular basalt with large phenocrysts of olivine, plagioclase and clinopyroxene, and frequently shows a sharp rim of a more vitric character.

A large number of pillows in this sector show multiple-rind structures as described by Kawachi & Pringle (1988), with meter-sized portions of old skins of pillows included within newly expanded pillows (Fig. 5). The nature of the contact between the sediments and the magma is clearly intrusive, as is evidenced by the presence of peperitic drops of basalt within a halo a few centimeters thick around the pillow border (Figs 6, 7). A petrographic study of this lithofacies shows a rapid cooling of the magma (development of perlitic jointing around thermal anisotropies represented by altered olivine phenocrysts), as well as drops of sediment within the basaltic glass.

In other cases there is an emission of digitate protrusions from the pillows into the sediment (Fig. 8). The coarse nature of the sediment hampers the identification of the vaporization effects in the sediments around the pillows. Also, the high porosity of the sediment may have enabled an easy escape of vapour, with only minor disturbances of the sediment laminae. In fact, important effects of vaporization on the sediment have been recognized in decimeter-sized sacks of sediment trapped and deformed between several pillows which are inferred to have formed simultaneously.

In the sector of transition between the central and northern zone several bodies crop out which show close-fitting upper pillow surfaces. They are covered by a thin (5–50 cm thick) discontinuous layer of calcarenitic sediments with a lamination that mimics the irregular morphology of underlying pillows. Laterally expanded pillows overlie these calcarenitic layers

Fig. 5. Close-up of an imploded pillow with a second glassy skin. Note the intrusive character of the pillow enhanced by suction of sediment during implosion (left of the hammer). Southern sector of Guardia Marina beach.

locally. The whole sequence is intruded by feeder dikes (Fig. 9), locally eroded beneath the overlying conglomeratic and calcarenitic sandstones.

Discussion

The northern sector of the Guardia Marina beach can be interpreted as a system of E-W dikes that reached the sea floor and created minor lava flows and pillowed flows. Two types can be distinguished among the pillows that formed at the magma–water interface: a toothpaste-like growth (sensu Walker 1992) mainly at the top of the dike, characterized by an antigravitative development of the pillows, and a tube-like growth mainly generated by spreading on dike flanks.

The occurrence of several dikes that show erosion at the level where the pillows were formed and the cross-cutting of a number of upper surfaces of pillow accumulations by younger feeder dikes, suggest a rapid recurrence of dike intrusion and consequently several episodes of pillow formation. The time-intervals between the episodes seem very short. The present level of erosion (sea level) could correspond to the level of the sea floor at the time when the pillows were formed.

A slow rate of subsidence prevents a rapid burial of the pillows. Hence, in a shallow environment, erosion of pillows generated at the magma–water interface is easier than complete preservation. Eroded pillows may have furnished the epiclastic component of the sedimentary filling simultaneously with the subaqueous growth of the pillows.

Sedimentary calcarenites pinch–out towards the northern sector, which may be interpreted as indicating that the magma of the main swarm of dikes has intruded at a higher level (Fig. 10). The presence of synsedimentary normal faults with little displacement may be explained in a similar way by the intrusion of dikes into layers of poorly consolidated sediment. Therefore, it is inferred that the intrusion of dikes is associated with a local and moderate uplift of earlier sediments, and that the faults represent readjustment

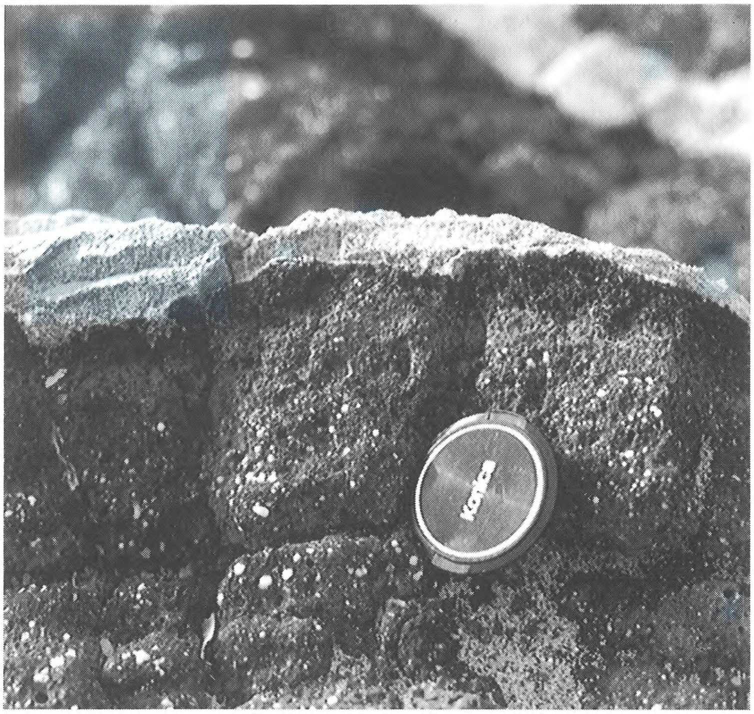

Fig. 6. Top of an intrusive pillow at the southern sector of Guardia Marina beach. Note the faulted vitric skin, without development of peperites.

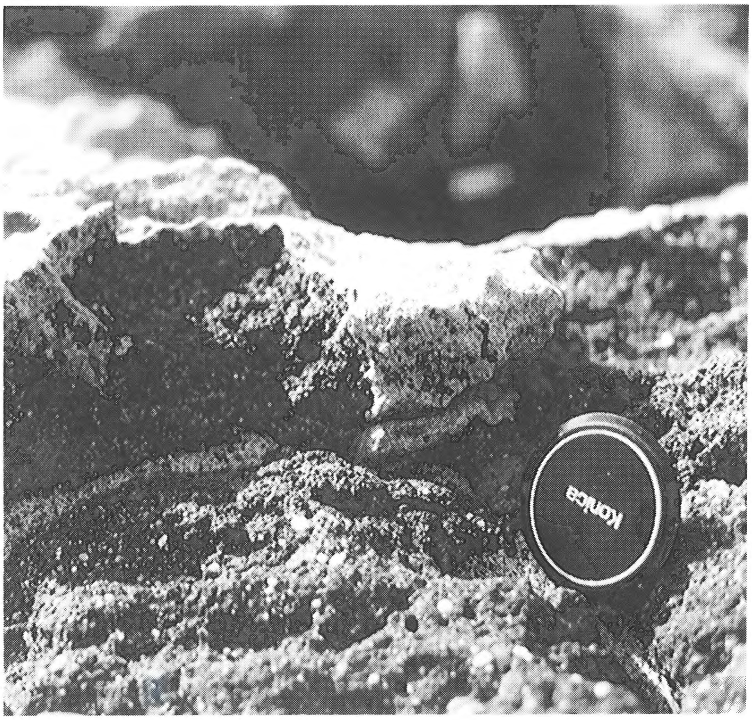

Fig. 7. Top of an intrusive pillow at the southern sector of Guardia Marina beach. Note the presence of peperitic droplets of basalt within the sediment and the inclusion of calcarenitic sacks within the pillow.

Fig. 8. Intrusive pillows at the southern sector of Guardia Marina beach. Note the emission of magma digitations from the upper pillow into the calcarenitic sediment, and the local presence of peperitic facies at the magma–sediment interface.

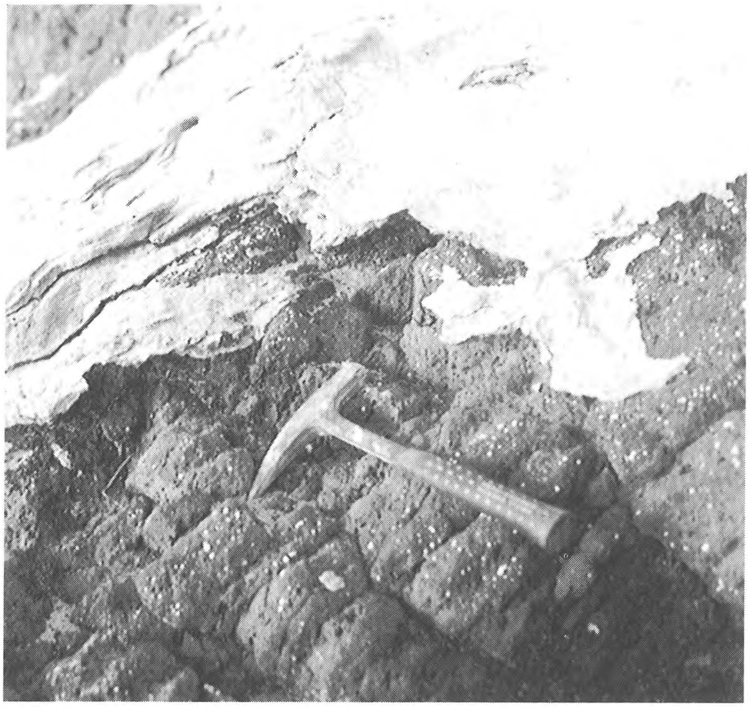

Fig. 9. Calcarenitic layers on eroded subvertically flow-banded dike (lower left) and pillows (upper right). Central sector of Guardia Marina beach.

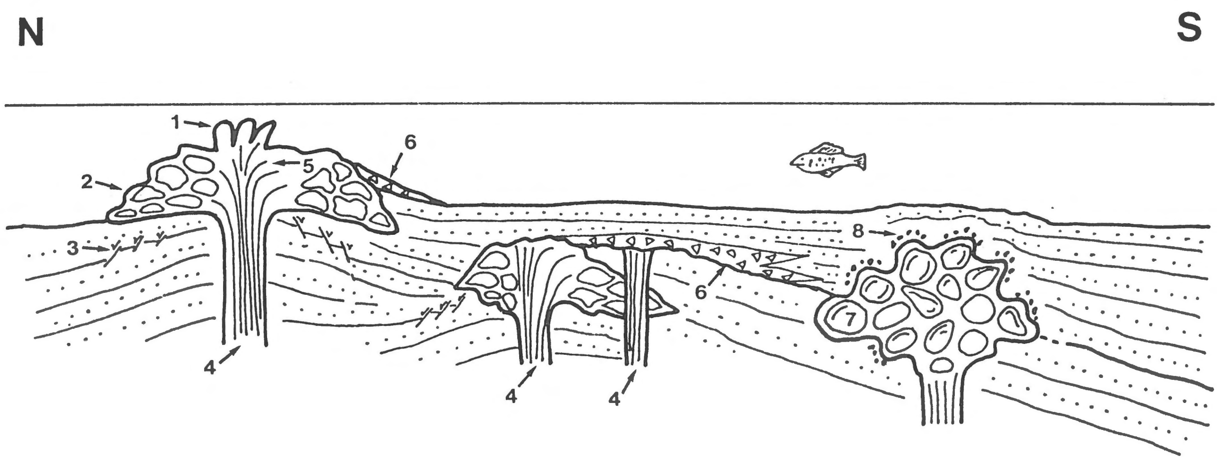

Fig. 10. Geological sketch (not to scale) of the pillow generation processes at Guardia Marina beach. Legend: 1. Toothpaste-like antigravitative pillows. 2. Highly vesiculate and hollow cupola-like pillows. 3. Synsedimentary faults. 4. Dikes with subvertical magmatic-flow banding. 5. Subhorizontal magmatic-flow banding. 6. Crystal-rich epiclastic layers related to early erosion of pillows. 7. Intrusive pillows with multiple-rind structure. 8. Peperitic lithofacies at the magma–sediment interface.

of local instabilities in the uppermost part of the pile of sediments.

The intrusive pillows associated with the development of peperitic lithofacies in the central-southern sector of the beach reflect a similar process, but mainly under a thin sedimentary cover. Imploded pillows may reflect a moderate to low lithostatic and hydrostatic pressure, as pointed out by Kawachi & Pringle (1988). This confirms the very shallow subaqueous environment evidenced by the fossil fauna and the sedimentological features (well sorted sandstones, paleoplacers, etc.) and the very thin sedimentary cover of the pillows.

The transition towards the northern sector of the beach is characterized by the development of pillows exclusively covered by a film of sediment only a few centimeters thick. At some places, the pillows emerging from the sea floor remained covered by the thin film of sediments. Elsewhere, a thin sedimentary film became sandwiched between the laterally spreading pillows. This phenomenon, together with the lateral continuity of the sedimentary layers (which were affected by intrusive pillows in the southern sector), points to the simultaneous growth of the pillows at the magma–water and the magma–sediment interfaces.

The study of the lithofacies in the Guardia Marina beach can be utilized to draw general conclusions about the physical constraints of the formation of subaqueous pillows, intrusive pillows, hyaloclastites and peperites.

Subaqueous pillows are generated at the water-magma interface because the vaporization of marine water is limited to a thin film of gas which is confined around the surface of the pillow skin. This phenomenon only allows a limited thermal transfer from the magma to the water, so that the magma remains liquid and the pillows can be formed by the interaction and subsequent immiscibility between two liquids of contrasted viscosity. The rheologic behaviour of the magma is directly related to the degree of crystallinity and hence to its temperature and composition. At high temperatures the degree of crystallization is low and the magma behaves as a Newtonian fluid. During the fall in temperature the proportion of crystals increases and the magma acquires a visco-plastic behaviour. When the volume of crystals reaches 65–70 %, the magma becomes brittle and has a solid-like behaviour (Fernández & Barbarin 1991). If, on the other hand, the hydrostatic pressure fails to confine this film of gas around the pillow, thermal transfer between magma and sediment is greatly enhanced by the continuous vaporization of water. Large volumes of magma cool rapidly with a sharp increase in magma crystallinity. Consequently, the magma acquires a brittle behaviour (hyaloclastite formation).

Intrusive pillows are very similar to subaqueous pillows. Therefore, we can infer that they are formed through an immiscibility process between two liquids of highly contrasted viscosity, the magma and the fluidized sediment. The process of thermal fluidization of sediment by vaporization of interstitial water has been described by Kokelaar (1982). Peperitic lithofacies are generated during the transition from the visco-plastic behaviour of magma and fluidized sediment to the brittle behaviour of magma.

Acknowledgements

Field work was partially funded by the University of Barcelona and Cirit Grants of the Autonomous Government of Catalonia (D.G.). The authors also acknowledge the funds granted by the Italian Ministero della Publica Istruzione (A.A.). Geochemical analysis and SEM+EDAX study of the samples was carried out at the Serveis Científico-Tècnics of the University of Barcelona. Microprobe analyses were also performed at the Centro Studi Geominerari e Mineralurgici del Consiglio Nazionale delle Ricerche (Cagliari). The preparation of samples was done at the Dept. Geoquimica, Petrologia i Prospecció Geològica and Servei de Làmina Prima, University of Barcelona. The authors sincerely thank all the scientific and technical staff at the institutions and laboratories that contributed to the development of this research. Frances Luttikhuizen provided useful linguistic improvements and suggestions on an earlier draft of the manuscript. Constructive reviews by H.N.A. Priem, G.P.L. Walker and an anonymous referee greatly improved the original manuscript.

References

Assorgia, A., S. Barca & C. Spano 1991 Upper Oligocene-Lower Miocene succession of the Arbus-Funtanazza coast (Southwestern Sardinia, Italy. In: B. Cappelli & D. Liotta (eds): Geologia del Basamento Italiano. Convegno in Memoria di T. Cocozza, Siena, 21–22 marzo 1991. Abstracts: 92–94

Assorgia, A., S. Barca, G. Onnis, F.A. Secchi & C. Spano 1988 Episodi sedimentari e vulcanici oligo-miocenici nel settore occidentale dell'Arcuentu e loro contesto geodinamico (Sardegna SW) - Mem. Soc. Geol. Italiana 35: 229–240

Assorgia. A., P. Brotzu, L. Morbidelli, E. Niccoletti & G. Traversa 1985 Successione e cronologia (K/Ar) degli eventi vulcanici del complesso calco-alcalino oligo-miocenico dell'Arcuentu - Periodico di Mineralogia 54: 89–102

Beccaluva, L., P. Brotzu, G. Macciotta, L. Morbidelli, G. Serri & G. Traversa 1989 Cainozoic tectono-magmatic evolution and inferred mantle sources in the Sardo-Tyrrhenian area. In: Boriani, A., M. Bonafede, G.B. Piccardo & G.B. Vai (eds) The Lithosfere in Italy. Advances in Earth Science Research. Accademia Nazionale dei Lincei, Roma, (540 pp): 229–248

Busby-Spera, C.J. & J.D.L. White 1987 Variation in peperite textures associated with differing host-sediment properties - Bull. Volcanol. 49: 765–775.

Cherchi, A. & L. Montadert 1982 The oligo-miocene rift of Sardinia and the early history of the western mediterranean basin - Nature 298 (5876): 736–739.

Coulon, C. 1977 Le volcanisme calco-alcalin cénozoïque de Sardaigne (Italie). Pétrographie, géochimie et genèse des laves andésitiques et des ignimbrites. Signification géodynamique. PhD Thesis, Université d'Aix-Marseille III, 1: 288 pp, 2: 70 pp

Cox, K.G., J.D. Bell & R.J. Pankhurst 1979 The interpretation of Igneous Rocks, Allen & Unwin, London, 450 pp

Fernández, A.N., & B. Barbarin 1991 Relative rheology of coeval mafic and felsic magmas: Nature of resulting interaction processes and shape and mineral fabrics of mafic microgranular enclaves. In: Didier, J., & B. Barbarin (eds) Enclaves and Granite Petrology. Elsevier, Amsterdam: 263–275.

Gimeno, D. & G. Onnis 1986 Procesos de asimilación de bioclastos (y su preservación) por parte de materiales piroclásticos en medio subacuático: dos ejemplos y un modelo genético - Acta Geol. Hispánica 21–22(2): 569–575

Kano, K.I. 1989 Interactions between andesitic magma and poorly consolidated sediments. Examples in the neogene Shirahama Group, South Izu, Japan - J. Volcanol. Geoth. Res. 37: 59–75

Kano, K. 1991 Miocene pillowed sills in the Shimane Peninsula, SW Japan - J. Volcanol. Geoth. Res. 48: 359–366

Kawachi, Y. & I.J. Pringle 1988 Multiple-rind structure in pillow lava as an indicator of shallow water - Bull. Volcanol. 50: 161–168.

Kokelaar, B.P. 1982 Fluidization of wet sediments during the emplacement and cooling of various igneous bodies - J. Geol. Soc. London 139: 21–33

Le Bas, M.J., R.W. Le Maitre, A. Streckeisen & B. Zanettin 1986 A chemical classification of volcanic rocks based on the Total Alkali-Silica diagram - J. Petrology 27: 745–750

Le Maitre, R.W. (ed.) 1989 A classification of igneous rocks and glossary of terms. Blackwell Scientific Publications, Oxford, 193 pp

Lonis, R. 1983 Rilevamento e studio geo-petrografico del settore meridionale del Monte Arcuentu. Unpublished Minor Thesis, University of Cagliari, 156 pp

Moore, J.G. 1975 Mechanism of formation of pillow lava - American Scientist 63: 269–277

Mullen, E.D. 1983 $MnO/TiO_2/P_2O_5$: a minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis - Earth Planet. Sci. Letters 62: 53–62

Pearce, J.A. & J.R. Cann 1973 Tectonic setting of basic volcanic rocks determined using trace element analyses - Earth Planet. Sci. Letters 19: 290–300

Savelli, C., L. Beccaluva, M. Deriu, G. Macciotta & L. Maccioni 1979 K/Ar Geochronology and evolution of the Tertiary "Calc-alkalic" volcanism of Sardinia (Italy) - J. Volcanol. Geoth. Res. 5: 257–269

Snyder, G.L. & G.D. Fraser 1963 Pillowed Lavas - U. S. Geological Survey Prof. Paper 454-B/C: 1–23/1–7

Walker, G.P.L. 1992 Morphometric study of pillow-size spectrum among pillow lavas - Bull. Volcanol. 54: 459–474

Yamagishi, H. 1985 Growth of pillow lobes. Evidence from pillow lavas of Hokkaido, Japan, and North Island, New Zealand - Geology 13: 499–502

Yamagishi, H. 1991 Morphological and sedimentological characteristics of the Neogene submarine coherent lavas and hyaloclastites in Southwest Hokkaido, Japan - Sedimentary Geology 74: 5–23.

Zuffardi, P., G.L. Del Bono & I. Salvadori 1956 Foglio Monte Arcuentu, Foglio 225 IV NO. Carta Geologica d'Italia 1:25.000, Roma.