PROVENANCE AND CHARACTERIZATION OF THE RAW MATERIALS OF LIME MORTARS USED AT SAGALASSOS WITH SPECIAL REFERENCE TO THE VOLCANIC ROCKS

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1. INTRODUCTION

The mortars used at Sagalassos have been discussed in a previous publication (Viaene *et al.* 1997). These mortars consist of a lime matrix and of various aggregates and admixtures. It was suggested that the lime originated from the burning (calcining at 800-1000 °C) and slaking (hydration of the burnt lime) of local Triassic limestones which are abundant in the area around Sagalassos. Three types of aggregates have been found so far in the mortars: limestone, crushed ceramics (chamotte) and volcanic fragments. The latter two are pozzolanic materials. The volcanic fragments consist of tuff and lava fragments, the first being a porous volcanic rock, the latter a dense volcanic rock.

Two main groups of lime mortars have been distinguished. Firstly, there are building mortars which consist of a lime matrix with aggregates mainly of volcanic origin. Secondly, there are mortars used in constructions that were related to water and these mortars consist of a lime matrix with (mainly) chamotte as an admixture. These admixtures (chamotte, volcanic rock fragments and volcanic powder) can be defined as pozzolanas, that is, siliceous and aluminous mineral substances which, though not having cementitious qualities themselves, will, at atmospheric temperatures in the presence of water, react with lime to form cementitious compounds (Blanks and Kennedy 1955) and give the mortar hydraulic properties. Such mortars can harden under water and obtain a higher strength than air-hardening lime mortars. The use of hydraulic lime mortars, first using volcanic powder and later also ceramic fragments, was already known to the Greeks in the sixth and fifth centuries BC and became more widespread during the fourth century BC (Viaene *et al.* 1997: 405). The Romans increased this knowledge of the hydraulic properties of mortars made of lime mixed with volcanic sands, which could harden under water and were an important element in the building of harbours and aqueducts. They also produced high quality hydraulic mortars made of a mixture of lime and chamotte. Their experiments with admixtures (*caementa*) eventually led to the introduction of 'Roman concrete' (Viaene *et al.* 1997: 406).

The previous study of the lime mortars from Sagalassos distinguished various raw materials: limestone, used both in the production of lime and as aggregates, and crushed ceramics and volcanic rock fragments (lava and tuff), that were used as admixtures. Thus far, the provenance of the different raw materials has been discussed in the framework of a broader study on the origin of the building materials themselves (stone, architectural ceramics, mortars, ...). The main aim of this paper is to identify the provenance of the various raw materials present in the lime mortars, based on petrographical, mineralogical and geochemical analysis. Special emphasis is given to the use of volcanic rocks as pozzolanic admixtures, because much work has already been done on limestones (Viaene *et al.* 1993) and on ceramics (Kucha 1995; Degeest 1997). The previous studies confirmed also that economic considerations at Sagalassos, particularly the problems of bulk transport over long distances, had forced builders to use local materials (Lamprecht 1987: 142), certainly in the case of chamotte and limestone (Viaene *et al.* 1997: 142). The lack of good sand may also have forced them to turn to volcanic materials as an alternative for use in building mortars, where strength in compression rather than hydraulic qualities, was needed (Viaene *et* *al.* 1997: 420, table 1). So far, the local provenance of these volcanic materials had not yet been established through comparative analysis. Therefore, a volcanic region of about 30 km^2 located immediately to the northwest of Sagalassos over the ancient mountain pass (Loots *et al.* 2000) was investigated to determine the characteristics of these rocks and to compare them with the admixtures used in the lime mortars. Only the southern part of this volcanic region, about 1 km to the north of the site, was examined during this study (Fig. 2).

2. GEOLOGICAL SETTING

On geological maps and in the field, five important stratigraphic units can be distinguished in the area around Sagalassos (Fig. 1). These are:
a – Mesozoic limestones (Trias-Jura): these form autochthonous and allochthonous series in the vicinity of Sagalassos. The limestone mountain range to the north of the site is part of an allochthonous nappe (Akdağ formation) and consists of white, mostly coarse crystalline limestone sometimes with chert layers and radiolarite.
b – An ophiolite sequence (Cretaceous): these occur as nappes obducted in the Tertiary (Eocene). This sequence consists of strongly serpentinised volcanic rocks and sediments. In the field, they are seen as considerably altered and weathered, mostly red-brown, rocks. The site of Sagalassos is located on an ophiolite sequence (not shown on the map).
c – A flysch sequence (Miocene): shales, marls, sandstones and conglomerates. Outcrops are present in the hills to the south of Sagalassos.
d – Volcanic rocks (Pliocene): tuffs and lava layers in a volcanic region to the northwest of Sagalassos and situated around Lake Gölçük (prov. Isparta). These volcanic rocks are deposited on a palaeo-relief of limestones.
e – Alluvial deposits (Quaternary): clays, sandstones, travertines and gravel present in the valleys around Sagalassos.

The volcanic region to the northwest of Sagalassos developed during the Tertiary-Quaternary volcanic activity in the western Taurides. According to Lefèvre *et al.* (1983) the volcanic region is of the Pliocene age (4.07 ± 0.20 to 4.70 ± 0.50 Ma using the K-Ar method). Lake Gölçük is supposed to be the eruption centre of this volcanic activity. The deposits consist mainly of lava layers and of volcanic tuffs.

3. MATERIALS AND METHODS

Samples were collected in the southern part of the volcanic region over an area about 5 km^2 (Fig. 1). Tuff samples were taken from various layers according to differences in colour, size and type of inclusions, compaction and resistance against weathering. Samples of a lava layer were also taken. In fact, only one lava layer could be distinguished in this part of the volcanic region, but lava layers occur more abundantly around lake Gölçük. That region, however, was not sampled systematically. Different sections (n=17) were made, with the intention of composing a lithological column for the southern part of the volcanic area.

Samples were examined by standard petrographical methods using polarized light. The porous samples were impregnated in a vacuum with a resin that was coloured with a blue dye. Characterization of the various mineral phases was carried out using a scanning electron microscope (SEM) and X-ray diffraction analysis (XRD). Chemical analyses were carried out by dissolving the samples in Li-metaborate and by estimating the concentrations of SiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, TiO_2 and P_2O_5 by atomic emission spectrometry (AES), using a Spectrojet III spectrometer. Na_2O and K_2O were analysed by atomic absorption spectrometry (AAS), using a Varian Techtron AA6 flame atomic absorption spectrometer. The loss on ignition (LOI) was determined by heating the sample from 105 °C to 1050 °C and determining the weight difference. On individual crystals (augites, plagioclases) a semi-quantitative chemical analysis was carried out using a scanning electron microscope (type JSM-6400) with an energy dispersive detector (SEM-EDX). Trace elements (Ba, Ce, Co, Cr, Cu, La, Nb, Ni, Pb, Rb, S, Sr, W, Y, Zn and Zr) were determined using X-ray fluorescence analyses (analyses carried out by Prof. J. Naud, Louvain-la-Neuve).

4. RAW MATERIALS OF THE LIME MORTARS: PROVENANCE AND CHARACTERIZATION

The various raw materials used in the production of lime mortars at Sagalassos will now be discussed. Since the limestones and the ceramics have already been intensively studied (Viaene *et al.* 1997), only a brief summary of the results will be given.

4.1. Limestones

Limestone is the raw material for lime production. Crushed limestone ($CaCO_3$) is first burnt at 800-1000 °C, which produces CaO and CO_2. This burnt lime (quicklime, CaO) is then hydrated by sprinkling water on it in 'lime pits' or by immersing a basket filled with quicklime in water until no further gas escapes ("dry-slaking", see: Kraus *et al.* 1989; for archaeological evidence see Viaene *et al.* 1997: 407). This slaked lime ($Ca(OH)_2$) is mixed with aggregates and admixtures and left to harden. If no pozzolanas are added and the lime contains no clayey impurities, the hardening will proceed by carbonation with CO_2 from the air ($Ca(OH)_2 + CO_2\ CaCO_3 + H_2O$). If on the other hand, pozzolanas are added or if the lime contains clayey impurities, then hardening is the result of hydration (with the forma-

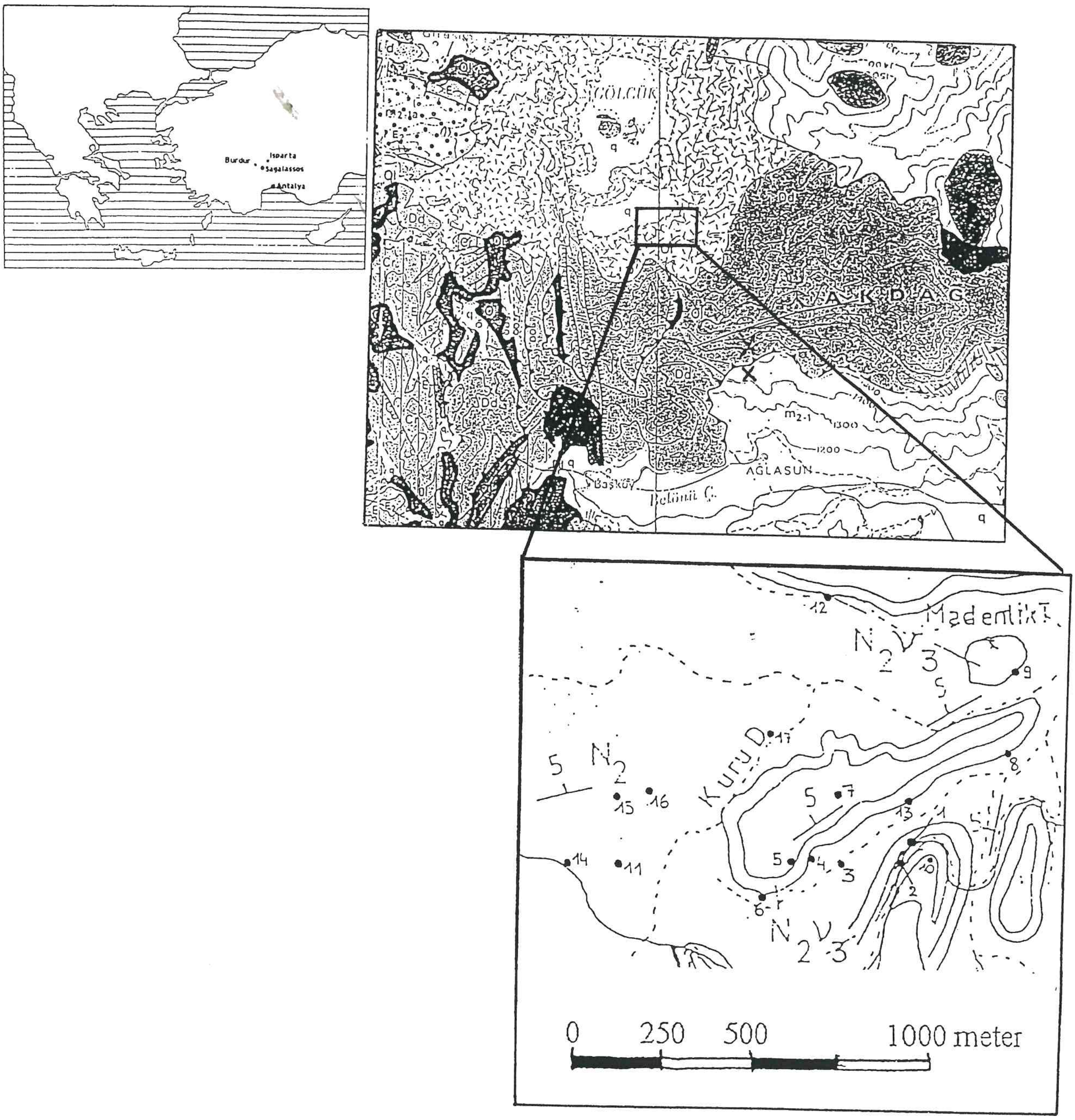

Fig. 1: Geological map showing the different tectonostratigraphic units around Sagalassos (**X**) (after Poisson *et al.* 1983). Scale: 1/100000. **Dd**: Trias limestone; **Ol**: Cretaceous ophiolite sequence, obducted in the Tertiary; $\mathbf{m_{2\text{-}1}}$: Miocene flysch; **v**: Pliocene volcanics; **q**: Quaternary alluvial deposits. The studied area of the volcanic region (indicated by the rectangle) is enlarged (Yalçınkaya, 1983) and the numbers refer to the different sections made. $\mathbf{N_2}$: Pliocene volcanics; $\mathbf{N_2v_3}$: Pliocene volcanic tuffs.

Fig. 2: View of the southern part of the volcanic region (studied area). Hills of loose, 'sandy' tuff can be observed on the slopes and the hard tuff layers form cliffs.

tion of hydraulic compounds) and only partly of carbonation (Adam 1984: 76; Lamprecht 1987: 135-140).

The limestone found around Sagalassos is fairly pure. White limestone or marble were preferred by the Romans as raw materials for their lime (Vitruvius, *De Architectura* II.5). Because lumps of lime were found in the mortars, one can conclude that this lime was dry slaked (Kraus *et al.* 1989).

The limestone fragments used as aggregates show the same characteristics as those identified in the building stone of Sagalassos (Viaene *et al.* 1993): veinlets of calcite, which are a general feature in the limestones around Sagalassos, recrystallized calcite (transformation from micrite into sparite), radiolaria and twinned calcite crystals. Both micritic (fine) and sparitic (coarse) limestones have been used. The same petrographic features are found in the limestones around the site, so the lime and the crushed limestones both originate from the local Triassic limestones, which are abundant in the locality (Fig. 1, unit Dd).

4.2. Chamotte

Crushed ceramics are used as pozzolanic admixtures in lime mortars. The practice of mixing crushed ceramics with a lime-based mortar to obtain mortars with hydraulic properties was well-known to both Greek and Roman builders (Viaene *et al.* 1997: 405-406). Architects of the Roman period used this type of mortar throughout the empire whenever volcanic sands (as pozzolanas) were not available and a hydraulic mortar was needed (Baronio *et al.* 1997). A limited reaction rim indicates the pozzolanic properties of the chamotte (Viaene *et al.* 1997).

The fabric of the crushed ceramics is similar to that of the locally produced common ware or coarse ceramics. The presence of hematite dust in the fragments makes them reddish to almost opaque. A wide variety of mineral inclusions is present in the chamotte: feldspars, quartz, partly or wholly decomposed micas, pyroxenes and amphiboles and, more rarely, rock fragments of limestone, sandstone and volcanics. The same petrographical features are found in the coarse ceramics produced at Sagalassos (Degeest *et al.* 1997). Whether crushed ceramics of a specific type were selected or whether the chamotte was simply randomly crushed common wares (rejected pottery, tiles or bricks), is not yet clear.

4.3. Volcanic materials

Volcanic sand and crushed volcanic fragments were also used as pozzolanic admixtures in lime mortars. Both Greek and Roman builders were familiar with the practice of adding volcanic sand to lime mixtures. In Greece, volcanic dust from Santorini was even exported as far as Athens for the production of a mortar which was resistant to water (Martin 1965: 424; Orlandos 1966: 150). With the addition of volcanic sand, at first that from the area around Mt. Vesuvius and particularly Pozzuoli, the Romans also obtained a high quality hydraulic mortar (Plinius, *Naturalis Historia* 35.16; Adam 1984: 37-78). The rocks from the volcanic region located to the northwest of Sagalassos (Fig. 1) will therefore be discussed as a potential possible raw material for the lime mortars used there.

4.3.1. Field observations

The volcanic region consists mainly of volcanic tuffs. These tuffs can be seen as hills of loose, 'sandy' material and of hard tuff layers (Fig. 2). They originate from the weathering and erosion processes of the tuff layers. The hard layers are easily distinguished in the field because they form cliffs. These layers dip gently towards the north (ca. 5 °N) and are deposited on a palaeo-relief of limestone.

The tuffs have a light-coloured matrix with many inclusions, such as pumice, lava and sandstone fragments, and mineral grains. Two types of tuff can be distinguished: a fine-grained tuff with very small inclusions (mm size) and a coarse-grained tuff that is very porous and contains large inclusions (up to 0.01 m size). The tuff layers are poorly sorted and have varying thicknesses. One lava layer was found in the studied area. It consists of a grey, fine-grained matrix with phenocrysts of pyroxenes, biotite, etc.

A composed lithological column, showing 13 different layers, was constructed based on differences in colour, type and size of inclusions, compaction and wether or not it followed the hard layers in the topography (Fig. 3). These correspond to 13 different eruptions. One andesite layer was also found in the study area. This lithological column forms a sequence which is representative of the southern part of the area under study.

According to the mode of transport of the fragments Philpotts (1990) distinguishes three groups of pyroclastic deposits: pyroclastic fallout, pyroclastic surges and pyroclastic flow. The tuff deposits around Sagalassos are pyroclastic flow deposits: they are poorly sorted, the deposits are thickest in depressions, inclusions are up to 0.1 m and the deposits show no internal structure.

According to Özgür *et al.* (1990) the volcanic activity in the Gölçük region can be divided into three stages (Fig. 4): (I) As a result of the development of a 'graben' system, a basic tephriphonolite was extruded near Lake Gölçük and was accompanied by local eruptions. The lavas of the tephriphonolite have since been intensively eroded. The second stage (II) is characterized by powerful volcanic explosions round the centre of the recent Gölçük caldera, resulting in great masses of friable tuffs, ignimbrites and pumice tuffs which dominate the recent landscape. Trachyandesite and trachyte are not found. After the explosive expulsion of a great part of the material from the magma chamber, the surface collapsed, thus forming the Gölçük caldera. Finally, isolated extrusions of trachyandesites and trachytes occurred (III) at various localities in the centre and in the surrounding area of the caldera (dikes, volcanic domes).

The first stage described by Özgür *et al.* (1990) is not clearly recognizable in the study area. Only one sample plots chemically in the field of tephriphonolite (see Fig. 11). However, most of the lava layers are situated around the lake Gölçük and that part of the volcanic area has not yet been systematically sampled. The tuffs of the area under study belong to the second stage. Because fragments of (trachy)andesite were found alongside intrusive fragments (syenite) in the tuff layers, a stage of lava extrusion must have occurred before the explosive eruption of the tuffs. Most of the lava fragments found in this study were trachyandesites and trachytes. The last stage corresponds with field observations and is visible on the geological map (Fig. 1) as isolated lava domes around lake Gölçük. A more detailed study of the volcanic region could better define the different stages of the volcanic activity.

4.3.2. Mineralogy and petrography of the volcanic rocks

Samples were analysed with X-ray powder diffraction on bulk samples. Anorthite and sanidine are the main phases and augite is abundant in all samples. Diopside and hornblende are present in small quantities in most samples while magnetite and quartz are accessory minerals.

With the scanning electron microscope titano-magnetite and pyrite are observed and the zoning of the plagioclases and the augites has been studied (see below).

Petrographically, the volcanic rocks consist of:
1 – a cumulate of mostly submicroscopic crystals and a glass phase. This cumulate is defined as the *matrix.*
2 – inclusions of varying size. These inclusions include polycrystalline particles, which we define as rock fragments and monocrystalline, mono-mineral inclusions.

- Matrix

The matrix consists of submicroscopic crystals, which are distinguished as anorthite and sanidine by XRD, and a glass phase. In thin sections individual needle-shaped crystals (ca. 0.01 mm – 0.03 mm) with Carlsbad twins or plagioclase twins are observed. The glass phase is visible as an isotropic substance. In thin sections, because of variations in the brown colours, this matrix has a cloudy appearance. In the matrix, inclusions such as rock fragments and crystals are dispersed. The size of these inclusions differs from sample to sample and varies from some 0.01 mm to some 0.01 m. The matrix is more important in the fine-grained tuff type.

- Inclusions

Pumice, lava fragments and sporadic sandstone fragments are observed as rock fragments in the volcanic tuffs. They do not appear in lava layers: only a matrix and monocrystalline inclusions (phenocrysts) can be distinguished. Pumice fragments (Fig. 5, compare also with Fig. 5 in Viaene *et al.* 1997) are very porous fragments with only a thin glass wall between the pores. This vesicular volcanic glass with spheric pores originates from high vapour pressure during explosive eruptions. Sometimes, crystals (biotite, augite) can be observed in these pumice fragments. The fragments are mostly rounded by the cooling in the air and as the result of friction with other fragments during eruption.

Lava fragments (andesite and trachyandesite) are observed as irregular dark coloured inclusions of different sizes (smaller than 1 mm to some 0.01 m) which are not porous. These fragments have also a fine-grained, submicroscopic matrix with different phenocrysts (Fig. 6, see also fig. 6 in Viaene *et al.* 1997). The crystals in the matrix (mostly needle-shaped) often show a lineation which indicates the direction of flow. The matrix consists of plagioclases and alkali-feldspars. The phenocrysts are identified as feldspars (plagioclases and alkali-feldspars), augite, biotite, magnetite and sporadically hornblende. The plagioclases and the augites are mostly zoned parallel to the rims. The crystals are very similar to the crystals in the tuff, except that the augite is more zoned in the lava fragments. The lava fragments have the same petrographic characteristics as the lava layers, which implies that these were mixed in with the tuffs during eruption.

Sandstone fragments only occur sporadically. A typical red-brown colour originates from the presence of iron oxides. In this red-brown matrix, quartz grains can be distinguished. These sandstone fragments may originate from the Tertiary flysch found in the vicinity and be included in the tuffs during an explosive eruption.

Plagioclases, alkali-feldspars, augites, diopsides, biotites and hornblendes are seen as individual crystals. Plagioclases (Fig. 7) and augites (Fig. 8, compare also with fig. 8 in Viaene *et al.* 1997) are strongly zoned parallel to the rim. The zoning of these minerals is caused by variation in their composition (more details in the next section).

4.3.3. Geochemistry of the volcanic rocks around Sagalassos

- Semi-quantitative chemical analysis of crystals

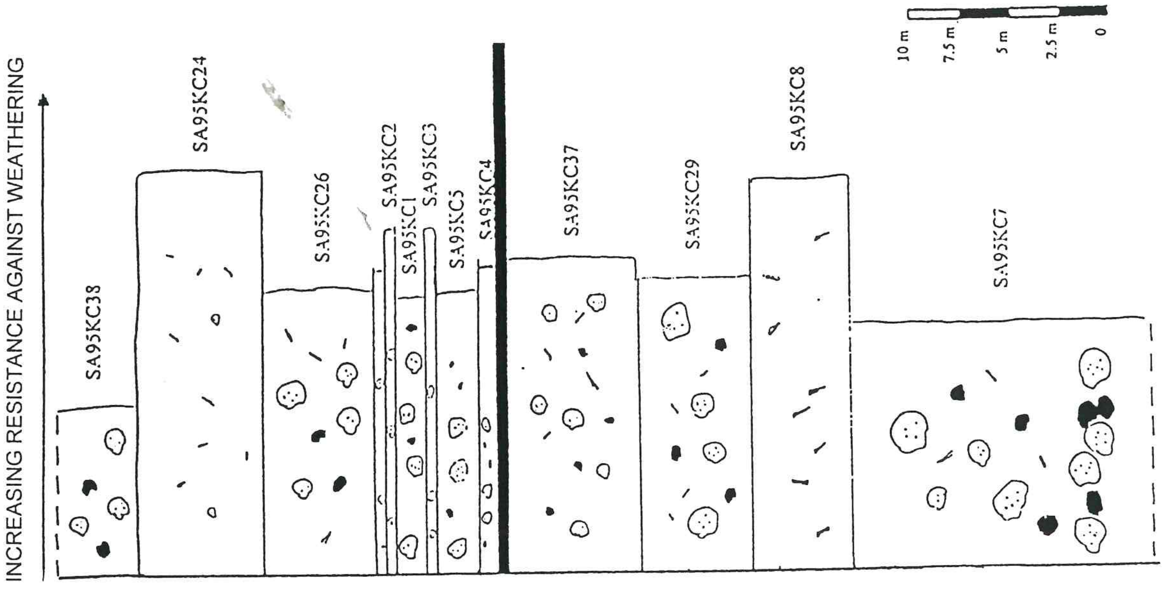

Fig. 3: Lithological column of tuff layers in the studied area. The lava layer (black) is the most resistant and the coarse-grained tuff (for example SA95KC27) is the least resistant against weathering. ⊙ = pumice inclusion; ● = andesite inclusion; ⟍⟋ = pyroxene or biotite inclusion; ▬ = lava layer.

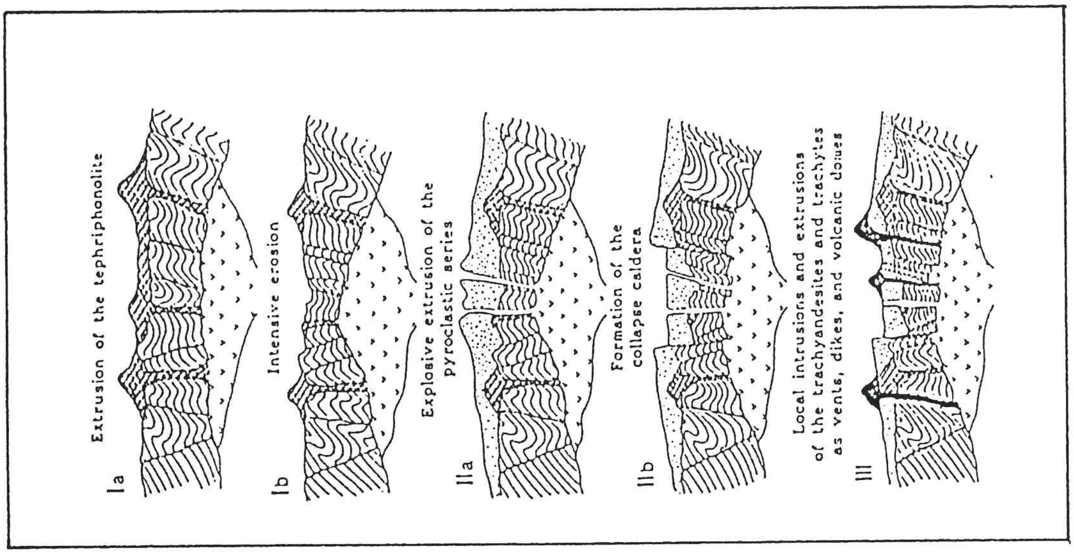

Fig. 4: Schematic evolution of the volcanic activity in the Gölcük area (Özgür *et al.* 1990). Not to scale.

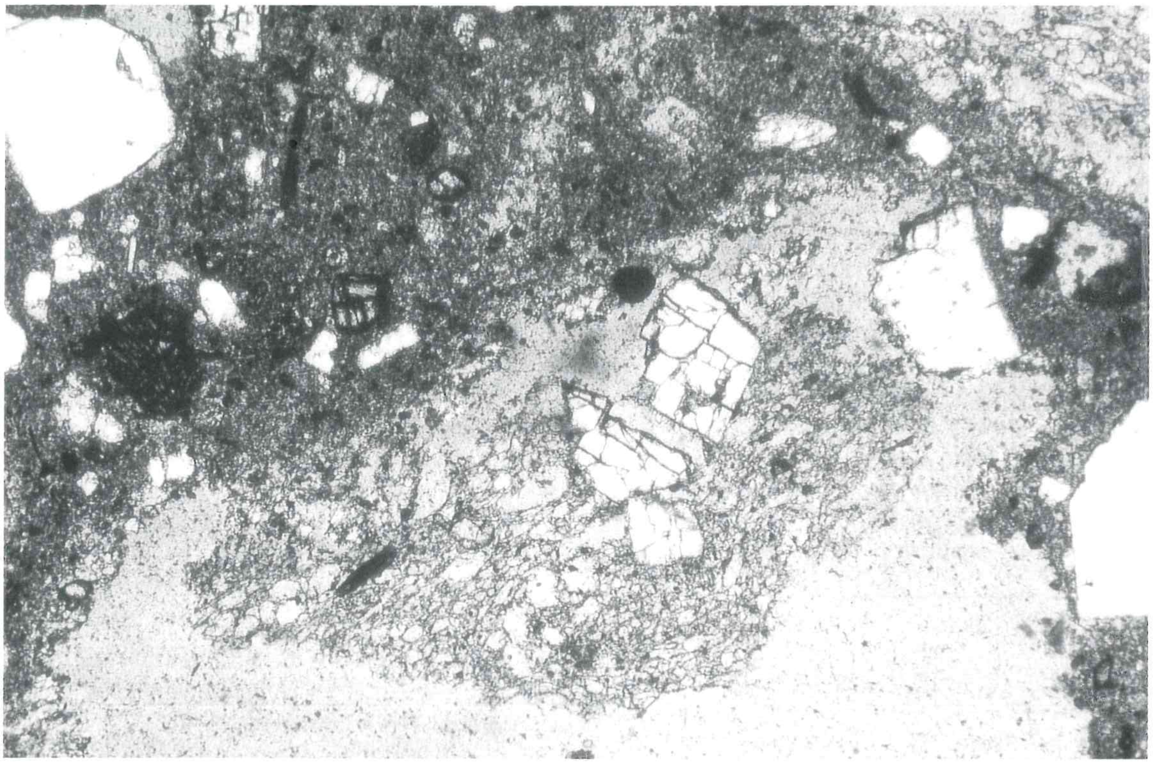

Fig. 5: Pumice inclusion in a tuff sample. The pumice is very porous and contains feldspar crystals (white). The pumice is partly gone due to preparation of the thin section. Sample SA95KC4. Scale: 1 cm = 625 μm.

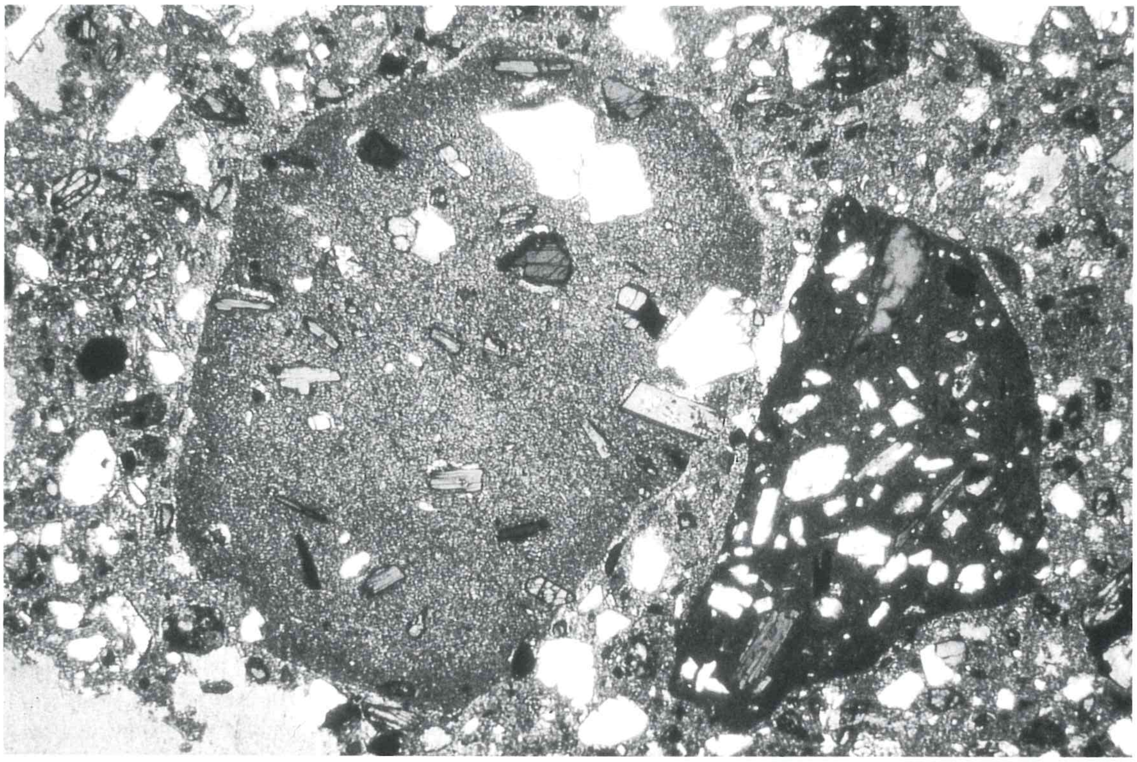

Fig. 6: Lava (andesite) inclusion in a tuff sample. The matrix of the lava inclusion is very fine and crystals of feldspar (white), biotite (brown) and augite (green) can be observed. Sample SA95KC4. Scale: 1 cm = 625 μm.

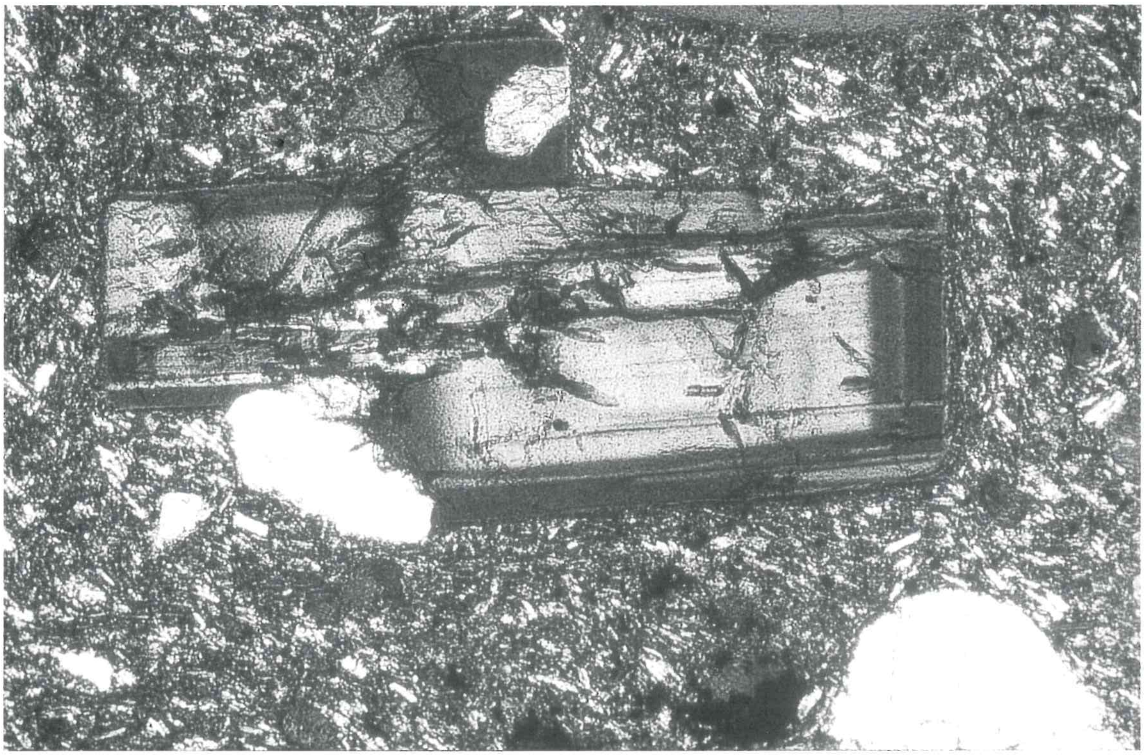

Fig. 7: Zoned plagioclase crystal in a fine-grained andesite matrix. The same crystals are also observed in tuff layers. Sample SA95KC42. Scale: 1 cm = 0.1 mm.

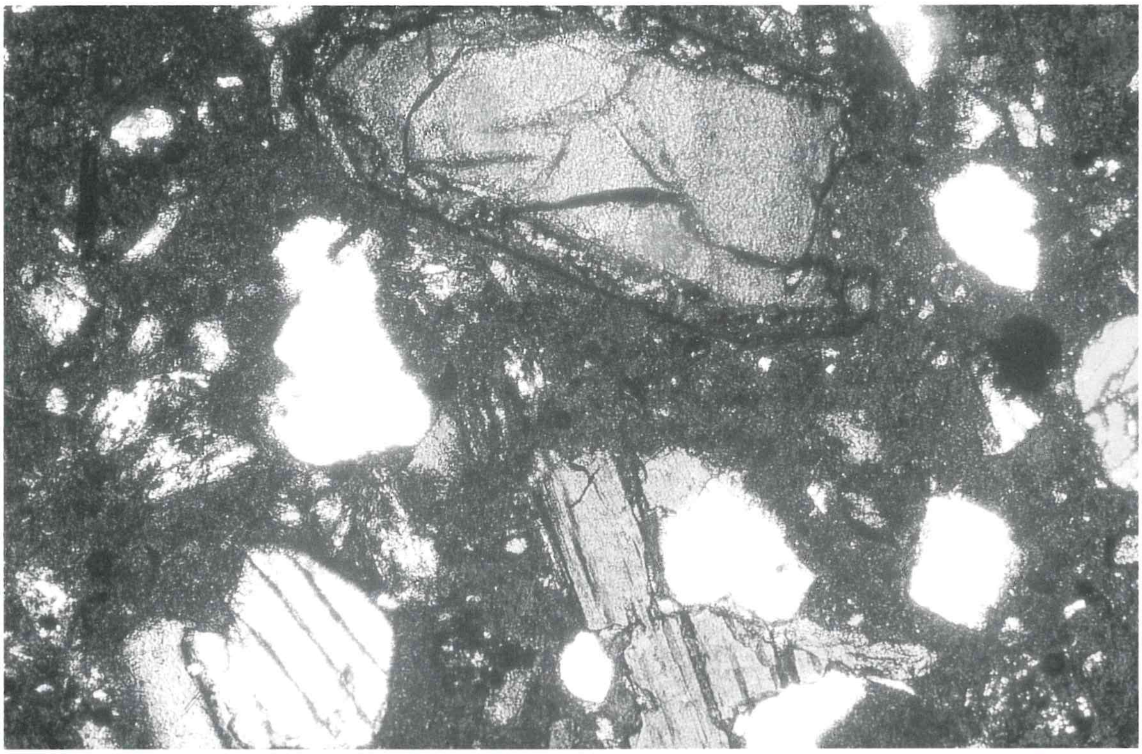

Fig. 8: Zoned augite crystal in a coarse-grained tuff layer. Sample SA95KC3. Scale: 1 cm = 0.1 mm.

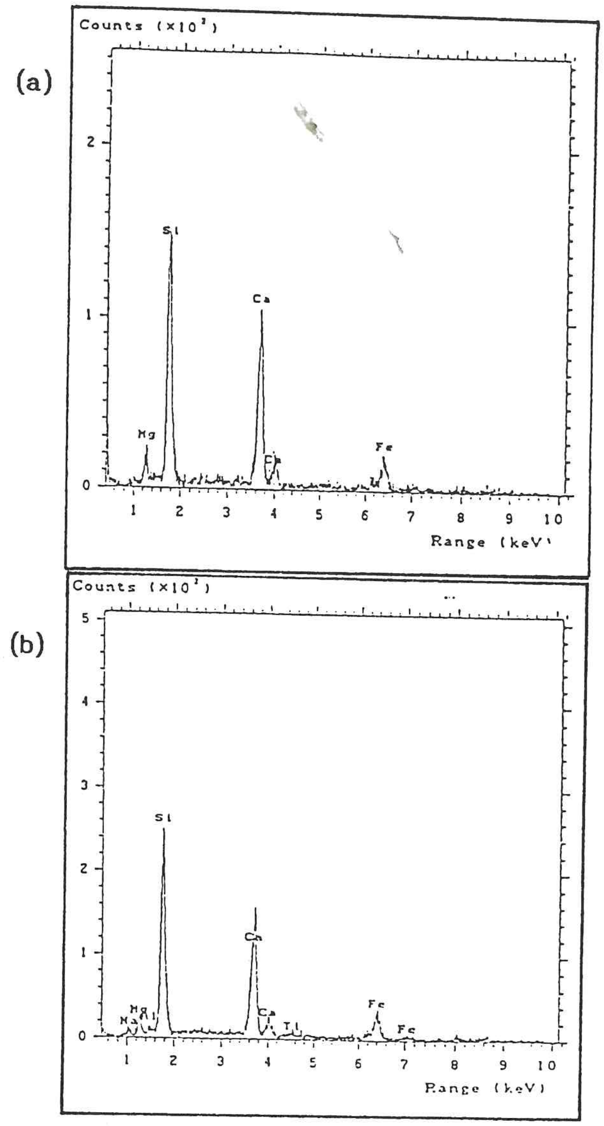

Fig. 9: SEM-EDX spectra of a zoned augite crystal. Sample SA95KC12. (a) core; (b) rim.

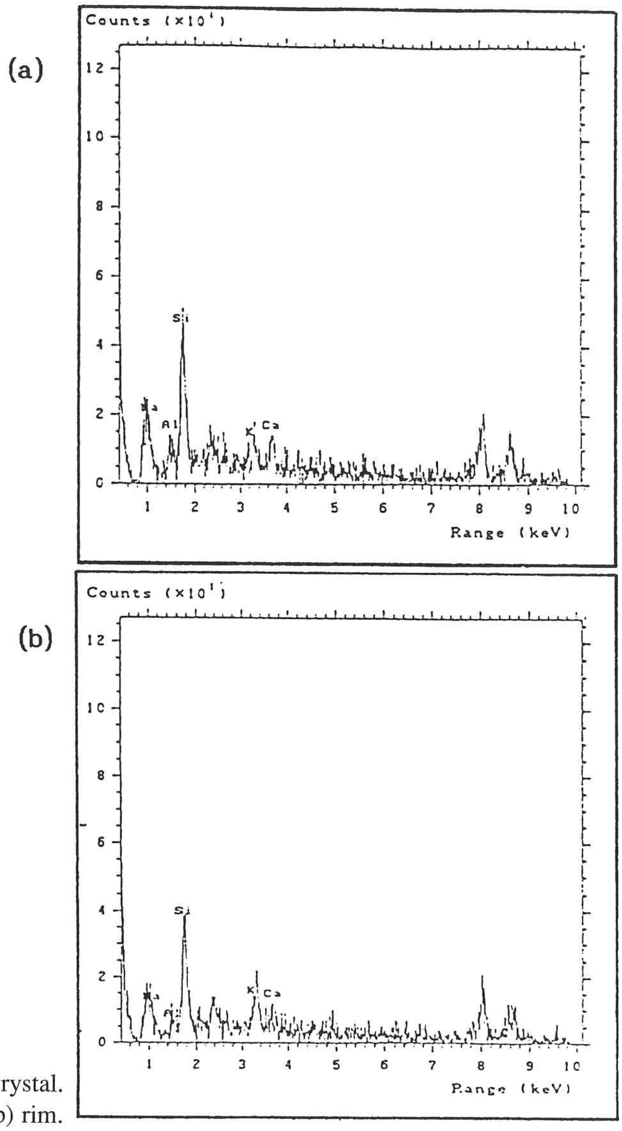

Fig. 10: SEM-EDX spectra of a zoned plagioclase crystal. Sample SA95KC11. (a) core; (b) rim.

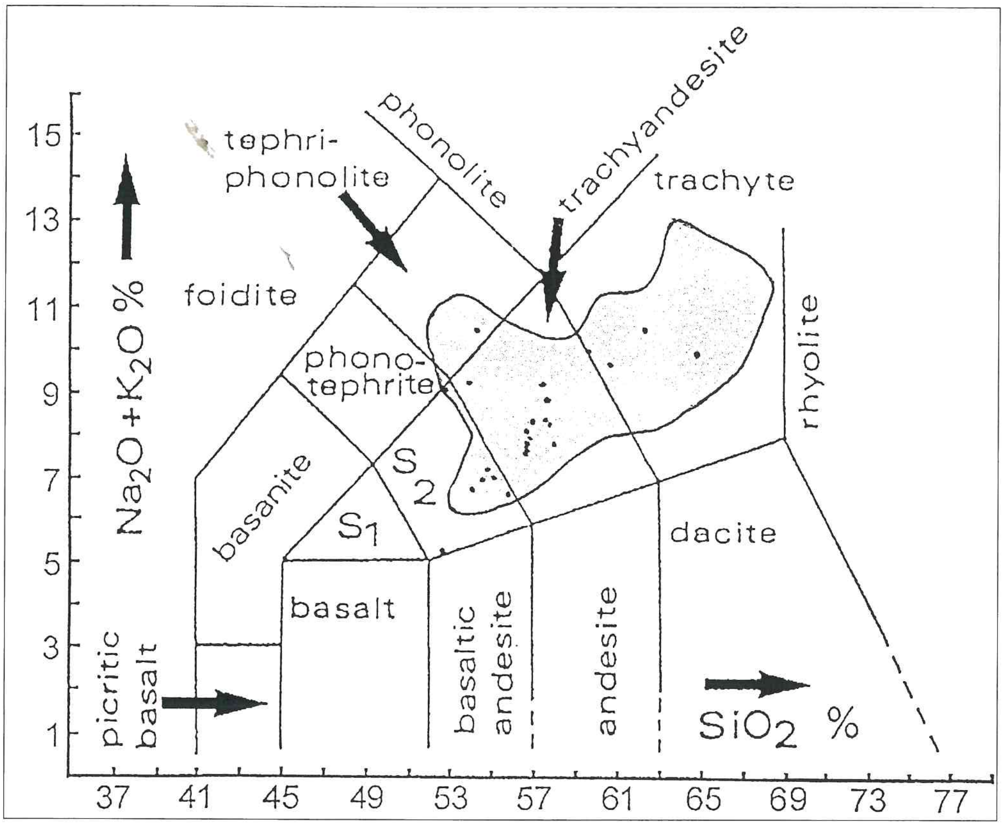

Fig. 11: Discrimination of the sampled tuff and lava layers (•) according to the classification scheme of Le Maitre (1984). The coloured area consists of samples analysed by Özgür *et al.* (1990). S_1: trachybasalt; S_2: benmoreite (Na) or shoshonite (K).

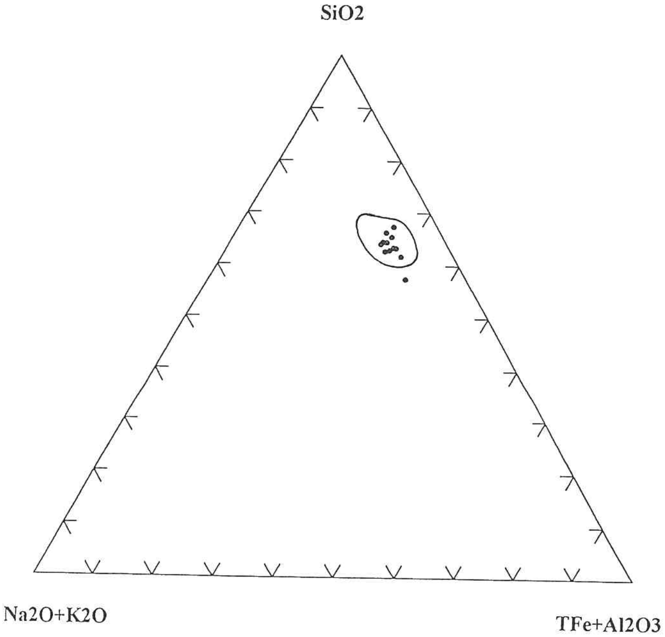

Fig. 12: Comparison of chemical analyses from lime mortars with only volcanic additives and rocks from the volcanic area. Mortar samples are identified by •. The encircled area contains the chemical analyses of volcanic rocks from the studied area.

With the SEM-EDX system, semi-quantitative chemical analyses on small volumes of plagioclases and augites were performed to characterize the zoning of these crystals. The zoning of augites (Fig. 9) is caused by a decrease of the Mg- and Ca-content and by an increase of the Fe- and Na-content from core to rim. The ratio of intensity of Si to Ca and Mg increases from core to rim (Si/Ca in the core is 1.3 and increases to 1.7 at the rim, Fig. 9). According to Deer *et al.* (1980) the first pyroxenes that crystallise have a diopside composition with a decreasing Ca-content and an increasing Fe- and Na-content during further growth. The zoning of the plagioclases is also caused by a variation in composition. The Ca- and Al-content decreases towards the rim while the K-content increases (Fig. 10). According to Deer *et al.* (1980) the zonation of plagioclases is often related to a Ca-rich core (bytownite) and a Na-rich rim. Here however, the ratio Si/Na is rather constant (Si/Na ca. 2 in core and rim). Quantitative analysis (e.g. with a microprobe) could characterize the zonation of the plagioclases.

- Chemical analyses of bulk samples from volcanic rocks
The results of the chemical analyses with AES and AAS are given in Table 1. The samples are classified by increasing SiO_2-content. The differences between the samples are not great, except for the SiO_2-content. The LOI-content is rather high and a distinction between lava and tuff can be made based upon this LOI-content. The LOI-content of the tuffs is higher than that of the lava samples. This high LOI-content can be explained by the loss of gases from the glass matrix and by dehydration of biotite and hornblende.

The higher Al_2O_3-content in sample SA95KC29 can be explained by the greater amount of feldspars which can be observed petrographically. The difference between the two types of tuff (fine-grained and coarse-grained) is not made clear through chemical analysis. The fine-grained tuff has a slightly higher K_2O-content and a slightly lower CaO-, MgO- and TFe-content. No evolution in composition relating to the lithological column (Fig. 3) can be seen.

In Fig. 11, the samples are plotted in a binary diagram, together with the field of data obtained by Özgür *et al.* (1990). All samples, except one (SA95KC29) plot within this field. Most of the samples are trachyandesites and trachytes, with some benmoreites or shoshonites. One sample (SA95KC16g) plots within the area of tephriphonolite, which could correspond with a relic of the first volcanic stage recognized by Özgür *et al.* (1990, see Fig. 4).

- Trace element analysis from volcanic rocks to the northwest of Sagalassos
Trace elements can be used to classify volcanic rocks and to determine the origin of the magma. The results of the analyses with XRF are given in Table 2. Very high amounts of Sr and Ba are observed. These amounts are higher than expected in volcanic rocks. Fisher and Schmincke (1984) mention an average value for Sr of ca. 300 ppm and for Ba of ca. 500 ppm. These high figures can be explained by substitution of Ba and Sr in feldspars. Rather high amounts of Ba can substitute in K-feldspars and Sr can substitute in feldspars in a range from about 100 to 5000 ppm (Yung *et al.* 1975). SA95KC8 especially shows an extremely high value of Ba and indeed more K-feldspars can be observed in this sample. Francalanci *et al.* (1990) mention Ba- and Sr-values of two ultra-potassic rocks around Isparta with values for Ba of 2384 ppm and 2354 ppm and for Sr of 2326 ppm and 2219 ppm. The values analysed here are clearly higher. Generally, we can conclude that the amount of most trace elements varies widely. Only elements in small quantities (Co, Cr, ...) show an almost constant value. Sulphur has a fairly constant value with the exception of two samples with high values. These samples contain more opaque minerals, including sulfides. More research on this subject is necessary for an explanation of the trace element content and for a better determination of the origin of the magma.

Trace elements can also be used to identify the provenance of the volcanic additives that were used in the mortars of Sagalassos. This will be dealt with in a following paper.

5. RELATIONSHIP BETWEEN THE VOLCANIC ROCKS AND THE VOLCANIC ADMIXTURES IN THE LIME MORTARS

The main aim of this study was to identify the provenance of the raw materials used in the lime mortars. The provenance of the lime and the chamotte is already clear. For the volcanic admixtures, the following observations could be made:
1 – petrographically, the volcanic rocks used as admixtures in the mortars and those from the volcanic region located immediately northeast of the city are similar. Both lava and pumice fragments are found in the mortars and in the tuff layers. The zoned augites and plagioclases, a characteristic feature in the rocks from the volcanic area, can also be observed in the mortars (compare Fig. 8 with fig. 8 in Viaene *et al.* 1997). The fragments in the mortars often have broken rims, so the inhabitants of Sagalassos must also have used the hard tuff and the lava layers, after crushing, instead of sandy tuff.

2 – chemically, the analyses of the mortars with volcanic admixtures only and the volcanic rocks from the volcanic region are also similar. This can be seen in Fig. 12, where the chemical analyses of mortars are plotted in a ternary dia-

Sample	SiO_2	Al_2O_3	TFe	MnO	MgO	CaO	Na_20	K_2O	TiO_2	P_2O_5	LOI	Sum	description
SA95KC16w	52.46	17.20	6.62	0.14	3.60	7.53	3.52	5.60	0.70	0.57	1.59	99.53	lava
SA95KC29	52.52	21.39	4.34	0.13	1.40	4.52	2.32	2.78	0.60	0.31	9.10	99.41	tuff (p)
SA95KC11	53.77	16.93	6.67	0.12	2.95	7.11	3.95	5.16	0.79	0.48	1.57	99.50	lava
SA95KC25	53.91	18.54	4.26	0.12	2.14	5.66	2.18	4.68	0.51	0.28	6.99	99.27	tuff (p)
SA95KC16g	53.99	16.45	5.42	0.13	3.41	7.81	4.30	5.77	0.70	0.56	0.83	99.37	lava
SA95KC44	54.37	15.69	5.89	0.12	2.85	6.44	2.98	4.07	0.62	0.38	6.08	99.49	tuff (p)
SA95KC33	54.68	17.09	5.31	0.10	2.96	6.16	2.61	4.57	0.64	0.36	4.94	99.42	tuff (p)
SA95KC48	55.61	15.20	5.41	0.11	2.79	6.61	2.44	4.38	0.61	0.36	5.99	99.51	tuff (p)
SA95KC32	56.42	17.36	4.65	0.11	2.66	4.93	2.82	4.99	0.60	0.32	4.46	99.32	tuff (p)
SA95KC26	56.44	16.78	4.08	0.11	2.05	5.33	2.66	5.11	0.55	0.35	5.68	99.44	tuff (p)
SA95KC5	56.52	16.29	4.65	0.12	2.20	5.76	2.72	4.98	0.59	0.30	5.18	99.31	tuff (p)
SA95KC4	56.53	16.41	4.56	0.13	2.07	5.57	2.79	5.02	0.58	0.28	5.41	99.35	tuff (p)
SA95KC1	56.54	16.23	4.57	0.13	2.42	5.46	3.15	4.91	0.59	0.27	5.09	99.36	tuff (p)
SA95KC7	56.66	16.42	4.72	0.14	2.29	5.65	3.01	4.90	0.58	0.31	4.65	99.33	tuff (p)
SA95KC2	56.85	16.15	4.37	0.12	2.33	5.78	3.09	5.08	0.57	0.27	4.78	99.39	tuff (p)
SA95KC43	57.15	18.05	4.82	0.16	1.94	4.44	3.84	5.34	0.53	0.28	2.77	99.32	tuff (p)
SA95KC30	57.19	17.40	4.78	0.12	2.67	4.77	3.45	5.04	0.57	0.27	2.95	99.21	tuff (p)
SA95KC31	57.31	17.49	4.71	0.11	2.63	4.64	3.48	4.98	0.59	0.29	3.02	99.25	tuff (p)
SA95KC3	57.42	16.31	4.51	0.11	2.14	5.08	3.97	4.94	0.58	0.26	3.97	99.29	tuff (p)
SA95KC8	57.86	16.59	3.44	0.18	1.86	4.26	2.65	5.27	0.44	0.22	6.54	99.31	tuff (p)
SA95KC39	59.32	18.03	4.67	0.13	1.81	4.30	4.78	5.27	0.57	0.35	0.17	99.40	lava
SA95KC24	60.53	17.46	2.49	0.08	1.09	3.09	4.24	5.40	0.34	0.16	4.27	99.15	tuff (p)
SA95KC12	62.18	17.01	3.85	0.08	1.42	3.54	5.49	4.94	0.47	0.19	0.19	99.36	lava
SA95KC42	64.66	16.85	3.60	0.05	0.79	2.39	4.83	5.18	0.48	0.24	0.43	99.50	lava

Table 1: chemical analysis results (weight%) of the volcanic rocks from the area to the northwest of Sagalassos. Tuff (p): porous coarse tuff type; tuff (f): fine compact tuff type; TFe: total Fe-content, expressed as Fe_2O_3.

Sample	Ba	Ce	Co	Cr	Cu	La	Nb	Ni	RB	Sr	W	Y	Zn	Zr	Pb	S
SA95KC1	3396	458	20	18	255	281	46	52	322	7498	41	17	71	363	116	119
SA95KC2	3787	475	19	25	326	282	41	45	229	8208	51	16	75	317	142	120
SA95KC3	3646	413	17	15	244	294	47	73	481	6525	50	19	77	380	107	112
SA95KC4	5248	481	20	19	377	302	45	50	229	8279	55	16	70	338	118	139
SA95KC5	3895	463	19	20	262	320	41	43	238	6990	64	14	68	320	103	183
SA95KC7	3346	488	19	18	228	298	44	35	142	7105	40	18	70	338	104	119
SA95KC8	13867	424	14	12	613	355	52	49	184	6084	40	14	83	406	98	175
SA95KC11	3311	563	17	19	195	498	56	56	102	5464	59	22	60	455	92	732
SA95KC12	2255	163	14	14	126	157	34	48	155	3679	59	13	44	383	69	100
SA95KC16	3658	431	19	27	218	312	36	38	97	5580	44	16	56	373	78	1493
SA95KC24	2292	330	13	19	146	233	35	33	176	3859	61	11	78	362	125	81
SA95KC29	4573	785	18	10	218	389	78	44	69	4852	36	32	80	596	115	133
SA95LC30	4649	568	20	29	227	363	37	48	172	4109	34	17	95	355	123	236
SA95KC42	1795	259	13	17	85	162	35	46	147	2008	88	16	43	376	78	96
SA95KC48	3074	499	20	27	189	304	34	41	168	4466	48	17	94	333	102	103

Table 2: trace element analysis results (ppm) of the volcanic rocks from the area to the northwest of Sagalassos.

gram which also includes the field of analyses of rocks from the volcanic region. Only elements which are characteristic for the volcanic rocks (SiO_2, Na_2O, K_2O, TFe and Al_2O_3) are plotted, so that there is no danger of misinterpretation from the lime matrix. All the mortar samples but one (SA94RO34) plot in the field of the volcanic rocks. From this it is suggested that the volcanic rocks of the study area were used as admixtures in the mortars. Further analyses of trace elements of mortars containing only volcanic rock admixtures could confirm the provenance of the volcanic rocks.

An experimental study on the mortars was begun in order to observe the influence of the different admixtures on lime mortars. Different mixtures of lime and volcanic rocks from the volcanic region or chamotte were made and the change in strength through time was observed. Preliminary conclusions were that mortars made with lime and volcanic admixtures reached a strength comparable to that of the Roman mortars from Sagalassos (Callebaut 1996). Further study of different mixtures is in progress.

6. CONCLUSIONS

As was to be expected for economic reasons, the raw materials used in the mortars of Sagalassos all have a local origin. The lime probably originates from Triassic limestones in the vicinity of Sagalassos. In fact, the limestone fragments that were used as aggregates show the same features as those of the Triassic limestone (veinlets of calcite, recrystallised calcite, radiolaria and twinned calcite crystals). The fabric of the crushed ceramics used as admixture is also similar to that of the locally produced coarse ceramics from Sagalassos. The same petrographical features are found. This paper focuses on the study of the volcanic rocks that were used as admixtures in the mortars of the ancient city.

There was a strong possibility that the volcanic rocks to the northwest of Sagalassos were a source of raw materials. These can be observed almost immediately north of the mountain pass as tuff layers with varying thickness and resistance against weathering. These hills consist of material which eroded from these tuff layers. Lava layers are only abundant around Lake Gölçük. According to differences in inclusions, i.e. size and type (lava fragments, crystals, sandstone fragments, ...), colour, compaction and whether or not the layer followed the hard layers in the topography, thirteen different eruptions could be distinguished in the southern part of the volcanic region. Petrographically, a matrix and different inclusions can be observed. These inclusions are divided into rock fragments (pumice, lava and sandstone fragments) and crystals (plagioclases, alkali-feldspars, augites, diopsides, biotites and hornblendes). Chemically, these volcanic rocks can be classified mainly as trachyandesite and trachyte.

Petrographically, the tuffs show features identical to those of the volcanic inclusions in the lime mortars. These inclusions consist of pumice and lava fragments which also occur in the tuffs. In the lava fragments from the mortar and from the tuffs strongly zoned augites as well as zoned plagioclases can be observed. Chemically, the tuffs and the volcanic admixtures also show the same range of content of SiO_2, Na_2O, K_2O, Fe_2O_3 and Al_2O_3, elements which are characteristic for volcanics. Thus, it is clear that the volcanic deposits located immediately to the north of the mountain pass (Loots *et al.* 2000) were exploited by the inhabitants of Sagalassos as mortar admixtures for their building projects. The area also contains an important limestone quarry of Roman imperial date (Waelkens *et al.* 1997: 46-47, fig. 40).

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