TMPM Tschermaks Min Petr Mitt (1986) 35: 217–242

TMPM Tschermaks Mineralogische und Petrographische Mitteilungen

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Petrology and Geotectonic Significance of Salic Rocks Preceding Ophiolites in the Eastern Vardar Zone, Greece

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With 12 Figures

Received March 23, 1985
accepted May 16, 1986

Summary

In the eastern Vardar Zone of Greece, Na-dominant salic rocks are intimately associated with ophiolites, constituting a NW-trending, about 8 km thick belt along the western margin of the Serbomacedonian Massif. Though of different ages and metamorphic histories, both contrasted lithologic units display similar lateral variations. The salic rocks vary from a hypabyssal tonalite-trondhjemite series in the NW into granophyres and submarine volcanics in the SE. The juxtaposed ophiolites change in the same direction from tectonite peridotites overlain or intruded by mafic-ultramafic cumulates into sheeted dykes and submarine volcanics. The salic rocks were formed by multi-staged fractional melting of a mafic source and correspond chemically to the low-K andensite rhyolite series. The geological and chemical evidence points at an immature island-arc setting for the salic rocks above a NE-dipping subduction zone. The lateral variations in their mode of occurrences probably reflect progressive attenuation of the continental crust. The corresponding variations displayed by the juxtaposed ophiolites may have resulted from a change in the plate motion from conservative in the NW to constructive in the SE.

Zusammenfassung

Petrologie und geotektonische Bedeutung der den Ophiolithen vorausgegangenen salischen Gesteine in der östlichen Vardar-Zone, Griechenland

In der östlichen Vardar-Zone von Griechenland bilden Na-betonte salische Gesteine und Ophiolithe einen NW-streichenden, ca. 8 km mächtigen Gürtel entlang des westlichen Randes des Serbomazedonischen Massivs. Trotz verschiedenen Alters und unterschiedlicher metamorpher Beanspruchung zeigen die beiden lithologischen Einheiten gleiche laterale Variationen. Die salischen Gesteine wechseln von Tonaliten und Trondhjemiten im NW zu Granophyren und submarinen Vulkaniten im SE. Die tektonisch angrenzenden, etwas jüngeren Ophiolithe variieren in der gleichen Richtung von Tektonit-Peridotiten und den überlagernden oder intrudierenden mafisch-ultramafischen Kumulaten zu einem Gangstockwerk und submarinen, vorwiegend basischen Vulkaniten. Die salischen Gesteine sind durch ein mehrphasiges fraktioniertes Aufschmelzen mafischen Materials entstanden und entsprechen chemisch der K-armen Reihe von basischem Andesit bis Rhyolith. Als Bildungsort weisen die geologischen und chemischen Kriterien auf einen inmaturen Inselbogen oberhalb einer nach NE gerichteten Subduktionszone während des Mittleren Juras hin. Veränderungen in den Ausbildungsformen der salischen Gesteine gehen offensichtlich auf ein progressives Verdünnen der kontinentalen Kruste zurück. Entsprechende Veränderungen in den gegenübergestellten Ophiolithen lassen sich durch Veränderungen in der Plattenbewegung von konservativ im NW zu konstruktiv im SE erklären.

Introduction

Several Mesozoic ophiolite belts are present in the innermost Hellenides. The eastern belt is associated with and preceded by a thick sequence of intermediate to acidic rocks. This ophiolite/salic rocks association forms a pertinent geological feature of Chalkidiki. It outcrops in the vicinity of Thessaloniki and extends in a SE direction for about 100 km (Fig. 1). The salic rocks were referred to by Kockel and Mollat (1977) as the "Chortiatis Magmatic Suite" after the Chortiatis mountains near Thessaloniki and this designation will be retained in the present work.

Regional Geology

A simplified geological map of Chalkidiki is given in Fig. 1. From this map, five lithological and structural units can be recognized. These units strike NW-SE and dip steeply towards NE, occasionally SW. They successively override each other through high-angle reverse faults. Each unit is characterized by own deformation and metamorphic history. In general, the age and metamorphic grade decrease from E to W as described below.

1) The old Paleozoic to Precambrian Serbomacedonian massif consisting of high-metamorphic rocks (gneisses, amphibolite, minor marble). Isolated bodies of serpentinites and metagabbros are irregularily distributed. This massif is intruded by several Mesozoic and Tertiary granites to monzodiorites.

2) A more than 5 km thick sequence of meta-sedimentary rocks ranging in age and facies from Permo-Triassic continental deposits in the E to Middle Jurassic geosynclinal flysch in the W.

3) The 4 to 5 km thick Chortiatis magmatic suite; to be described in the following chapter.

4) A discontinuous ophiolite belt comprising the Thessaloniki and the Sithonia ophiolites. The Thessaloniki ophiolite includes five major and disconnected protrusions that consist of peridotite, websterite and gabbronorite in variable proportions and different internal structures. The Sithonia ophiolite is presented by a sheeted dyke complex, submarine volcanics and a coeval Upper Jurassic sedimentary succession.

5) The westernmost unit is defined by the Upper Jurassic transgression. The basement is locally exposed and includes a slab of the Serbomacedonian Massif, the Upper Jurassic granite of Monopigadon and the small ophiolite occurrences at Oreokastron and Kassandra. This unit is largely covered by Tertiary and Quaternary sediments.

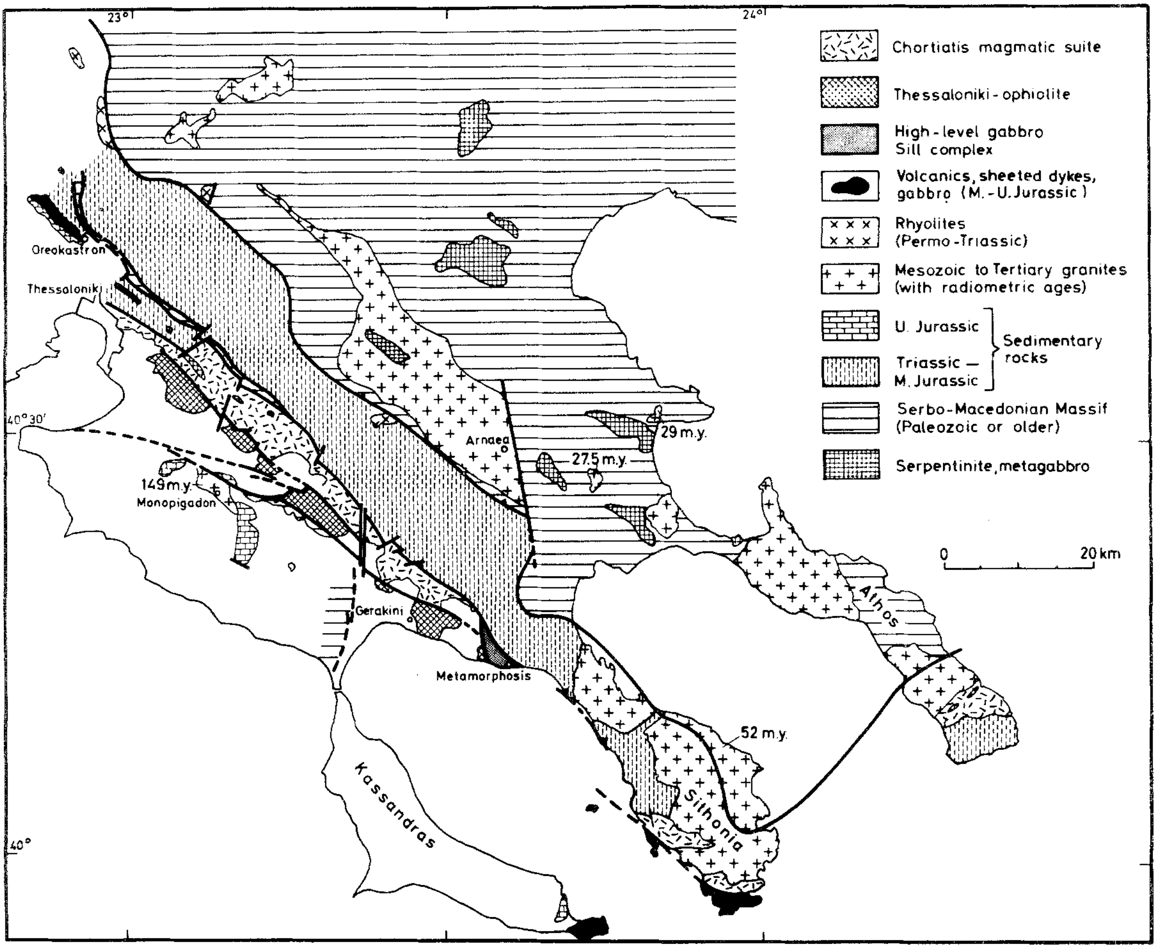

Fig. 1. Geological sketch map of Chalkidiki (simplified after Kockel et al. 1971)

Paleogeographic and Age Relations

A short account of the Mesozoic paleogeography at Chalkidiki was given by Mussallam and Jung (in press). According to these authors, an intracontinental rift was developed along the western margin of the Serbomacedonian Massif at the end of the Paleozoic and persisted until the Middle Jurassic. The Permo-Triassic arkoses and fanglomerates and intercalated rhyolites (Kockel et al. 1971; Mercier 1973) probably define the onset of rifting. Shallow-water carbonates prevailed during the whole Triassic. The subsidence achieved its maximum in the Lower Jurassic as evidenced from the occurrence of radiolarian cherts alternating with thin-bedded limestones. Volcanic activity is presented by a few hundred meters thick tholeiitic basalts. Sedimentation terminated with the deposition of a 3–4 km thick flysch apron (Svoula Flysch). At Sithonia, some highly altered basaltic sheets showing MORB chemistry are intercalated with this flysch. Fossils were not found in the Svoula Flysch. It is evidently younger than the Lower Jurassic and possibly includes most of the Middle Jurassic.

The rift was closed before the early Upper Jurassic as suggested by a radiometric age of 149 m.y. of the westerly flanking post-orogenic granite at Monopigadon (Fig. 1). In addition, most of the detrital material for the Kimmeridgian to Tithonian transgression was supplied by the meta-sedimentary rocks of this rift. There is no sedimentological or palaeontological record for the interval between the rift closure and the Upper Jurassic transgression at central Chalkidiki. It is just during this unrecorded interval that the Chortiatis magmatic suite and the juxtaposed Thessaloniki ophiolite were here emplaced. The lower degree of deformation displayed by the Chortiatis magmatic suite suggests that it was formed shortly after a major orogenic phase that resulted in the penetrative deformation of pre-existing rocks and in the premature closure of the Mesozoic rift. Subsequently, this suite was subjected to a later phase of pre-Tithonian deformation and lower greenschist-facies metamorphism. This phase predates the emplacement of the associated ophiolites which are not affected by it. Radiometric dating on a post-emplacement perigranitic pegmatite in the Thessaloniki ophiolite gave an age of 156 m.y. (Kreuzer, personal comm.). The age obtained from a hornblende gabbro dyke in this ophiolite is 172±5 m.y. (Kreuzer, personal comm.). It can be deduced from these data that the emplacement of the Thessaloniki ophiolite took place during the latest Middle to earliest Upper Jurassic. Whilst the central Chalkidiki has existed as a land mass partly covered by the Upper Jurassic epicontinental sea since the late Middle Jurassic, an actively spreading center was in formation at Sithonia.

Geology

The Chortiatis magmatic suite is in tectonic contact with its surroundings. Adjacent to the Thessaloniki ophiolite, it is isoclinally folded with almost vertical to strongly west- and northwest plunging fold axes.

Along strike, this suite varies from tonalites and trondhjemites in central Chalkidiki to granophyres and submarine volcanics at Sithonia. Intermediate and acidic sills are interlayered with these rocks, whereas dykes are restricted to a few occurrences of dm-thin aplites.

Sills

The sills are gray to greenish gray fine-grained subparallel sheets that range in thickness from a few cm to more than 5 m. They are mostly concordant with the structural grain of Chalkidiki. Their present attitudes vary slightly about a well-pronounced maximum of 115°/80° NE.

At central Chalkidiki, the sills contribute with about 50% to the whole sequence, and at some levels they may be the only rock present for several tens of meters. At least three sill generations can be distinguished here. The older sills are usually also the thicker (in average more than 2 m thick). The younger and thinner sills are frequently emplaced within the previous ones. The multiple injections and chilling textures are reminiscent of the diabasic sheeted dykes in many ophiolites. There is ample evidence that the tonalitic-trondhjemitic hosts were also formed by multiple intrusions but the temporal and volumetric relations of these intrusions are obscured by the sills.

At Sithonia, the sills predominate over their granophyric hosts which are mostly present as narrow screens. Chilling is less obvious. Some sills occur also at higher levels within the volcano-sedimentary succession. Pyrite is a distinctive mineral of both the sills and the overlying volcanics.

Volcanics

Volcanic rocks are rare in the Chortiatis suite of central Chalkidiki. The inclosed tuffaceous and coarse pyroclastic horizons here belong to older, probably subaerial eruptions. At Sithonia, the volcanics constitute an about 2 km thick succession of pillowed and non-pillowed lava flows with minor pyroclastic horizons overlying the granophyres. The boundary between both is irregular and gradational. NE-striking inclined sheets and discordant dykes are not uncommon. The pillows measure 1 to 2 m in cross section and contain abundant epidote-filled amygdules in their rims. A few cm thin schlieren of jasper may be present. The frequent intercalations of argilaceous sediments and radiolarian chert point at deep-water conditions.

Sedimentary Rocks

In addition to the thin intercalations, over 100 m thick sedimentary successions occur at two levels within the volcanic pile of Sithonia. Both sedimentary units have a limited lateral extent and are evidently younger than the penetratively deformed, tectonically bordering Middle Jurassic Svoula Flysch. At the other hand, they are almost indistinguishable from the Upper Jurassic sedimentary rocks of the adjacent Sithonia ophiolite. The lower unit consists of shales and siltstones alternating with limestones and grading upwards into either turbidite or massive limestones. Large nodules (with diameters in excess of 1 m) of reddish brown jasper with abundant Fe-Mn oxides occur in its lower part which is locally intruded by up to 40 m thick intermediate sills. The sills have introduced a weak thermal metamorphism with almandine-rich garnet and minor Cu-mineralization in the shales. Microprobe analyses reveal the composition $(Fe_{0.60}Mg_{0.02}Mn_{0.20}Ca_{0.19})_3Al_{1.95}Si_{3.04}O_{12}$, corresponding to the composition $Alm_{59.5}Pyr_{2.0}Spess_{19.9}Gross_{18.6}$. The upper, 150 m thick unit, is also developed as shales overlain by graded-bedded and conglomeratic sandstones. Intercalations of pillowed lavas and massive andesitic flows are characteristic. In both units, a volcanogenic component is lacking. The terrigeneous material is attributed to the high input of elastics from a nearby continental terrane.

Xenoliths

A wide variety of xenoliths of sedimentary, metamorphic and magmatic origin is present in the Chortiatis suite of central Chalkidiki. The xenoliths are mostly aligned parallel to the regional strike. They range in diameter from a few dm to several km.

Among the xenoliths of sedimentary origin, the calcareous ones display the most pronounced contact-metamorphism with either of the following parageneses:

salite + wollastonite + vesuvianite + epidote
diopside + wollastonite + andradite + epidote

The pelitic and psamitic rocks are usually silicified. Their irregular and patchy banding probably corresponds to relic foliation. Some sandstones are present as diopside-garnet hornfels with considerable amounts of authigenic microcline.

Mafic and ultramafic xenoliths include gabbro, pyroxenite, and peridotite. The gabbroic and pyroxenitic xenoliths usually show irregular outlines. Some sills are chilled against them. In other cases, the xenoliths are surrounded by a graditional zone which consists of plagioclase and quarz, suggesting that some reaction has occurred. Melting textures were, however, not observed. The 0.1 to several km large peridotites are altered into serpentinite and are commonly associated with garnet-tourmaline-muscovite schists. The smaller, a few dm measuring ones occur as nodules of talc-schist. The nodules are rimmed by muscovite- and actinolite-bearing chlorite schist. Similar xenoliths in acidic rocks have been described by Philips and Hess (1936) and by Rost (1966), who explain the rims as the result of metamorphic differentiation, a conclusion also supported by the present authors. In the case of xenolithic chromite and diopside grains in some acidic sills, a reaction with the melt is strongly suggested.

The mafic and ultramafic mega-xenoliths are tectonically sliced within the Chortiatis magmatic suite. They probably present parts of the mafic and ultramafic bodies in the Serbomacedonian Massif.

Petrography

The normative composition of the Chortiatis rocks is shown in Fig. 2. According to the nomenclature of O'Connor (1965) the majority of these rocks classify as tonalites and a minor amount as trondhjemites. In the *Qz-Or-Pl* triangle, they plot in the fields of diorite and tonalite-trondhjemite after the classification of Streckeisen (1976).

Gabbro-Tonalite

These rocks range from gabbro through gabbrodiorite to diorite and tonalite. They are grouped together because of the complete mineralogical gradations between them. The texture is usually hypidiomorphic-granular with an average grain size of 0.8–2 mm. Pyroxenes are abundant in the basic members of this group. Characteristically, only Ca-rich clinopyroxenes are present. The clinopyroxene shows diopsidic compositions and occurs as up to 2 mm large, twinned, not exsolved grains. With increasing silica content in the whole rock, it is progressively replaced by actinolitic hornblende. Relic pyroxenes are, however, still present at 60 wt.% SiO_2.

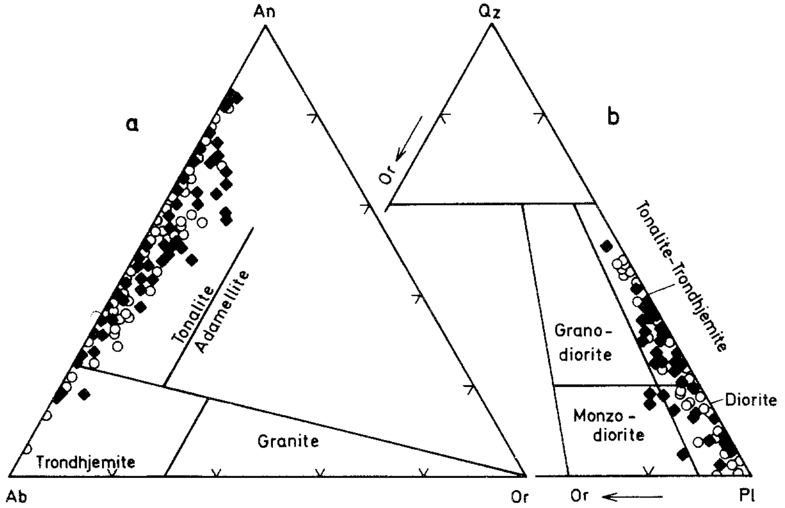

Fig. 2. Normative composition of the Chortiatis rocks. Open symbols = tonalites, trondhjemites, and granophyres; closed symbols = sills. a) After O'Conner (1965); b) after Streckeisen (1976)

In the SiO_2-rich diorite and tonalite the modal amount of amphiboles decreases significantly to 15–20%. As noted by Koopmann (1982) the amphiboles change their composition from actinolite and actinolitic hornblende replacing clinopyroxene in gabbro and gabbrodiorite into Mg- and Fe-hornblende crystallizing directly from the melt in tonalite and trondhjemite. The plagioclasse (14–55% *An*), originally displaying oscillatory zoning is mostly replaced by zoisite or clinozoisite.

Alteration is moderate to strong in the gabbroic and weak in the tonalitic rocks. Most of the gabbros are saussuritized with the plagioclase being invariably replaced by epidote, the pyroxene by actinolite. Chlorite is most abundant in the more acidic varieties.

Trondhjemites

These leucocratic rocks display fine-grained (0.6–1.5 mm) hypidiomorphic granular textures with oligoclase (14–20% *An*) and quartz as the major constituents. Greenish brown hornblende may be present in amounts not exceeding 10%. Biotite exhibiting all stages of replacement by chlorite occurs less frequently (2–3%). This replacement evidently took place prior to the penetrative deformation of the trondhjemites. Other accessory minerals include apatite, sphene and Fe-Ti oxides. Alteration is generally not as intense as in the gabbro-tonalite rocks. The core of the weakly zoned oligoclase may be replaced by fine-grained epidote, sericite and/or by prehnite. The hornblende is usually less affected by this alteration and only in a few instances a peripheral replacement by chlorite can be observed. In foliated trondhjemites, the texture is typically schistose with abundant epidot, chlorite and locally grossularite-rich almandite.

The intergrowths of plagioclase and quartz present a typical feature of these trondhjemites (Koopmann 1982). Similar intergrowths were described from oceanic plagiogranites (Coleman and Donato 1979). Their origin, whether due to simultaneous crystallization of plagioclase and quartz or whether it is the result of metasomatic replacement of the one mineral by the other, is a matter of debate. Two types of intergrowths can be recognized: In the *graphic intergrowths* either of both minerals is intergrown with the other. Where the subordinate quartz is intergrown with plagioclase, it displays regular outlines. Where the plagioclase is intergrown with quartz, it is also subordinate but it typically shows irregular outlines. Both varieties may occur adjacent to each other. Their differently oriented plagioclase grains are then connected by quartz which extends in the same optical continuity over three or more intergrown grains. The amount of plagioclase in this several mm measuring "quartz crystal" varies from 30 to 60%.

In the *myrmekite-type* intergrowths the ratio of quartz to plagioclase fluctuates about unity. Commonly, the an- to euhedral plagioclase, which may be also myrmekitic, acts as a "nucleous" for these intergrowths. In a few instances, quartz appears instead of plagioclase. Some rocks consists almost entirely of plagioclase-cored myrmekites. The Na_2O content achieves a value of 6.2% at 72.6% SiO_2.

Granophyres

The granophyres have their main distribution at Sithonia. They are present in minor amounts in the northern occurrences. These rocks correspond mineralogically to the trondhjemites, but they exhibit a prophyritic texture. The up to 1 mm long phenocrysts of prismatic plagioclase (*An* 22.9–28.6) are embedded in a fine-grained (0.05 mm) groundmass of albite and quartz, which may be micrographic intergrown. This porphyritic texture is possibly the result of progressive "myrmekitization" of plagioclase and quartz.

Blue-coloured ferro-tschermakite of composition $(Na_{0.3}K_{0.1})(Ca_{1.89}Na_{0.11})(Mg_{0.63}Fe_{3.15}Ti_{0.03}Al_{1.37})(Al_{2.06}Si_{5.93})O_{22}(OH)_2$ occurs as 0.6 mm long grains in amounts less than 10%. Biotite or muscovite may be present locally. The granophyres are strong foliated and mostly metamorphosed into greenschists. The secondary minerals include chlorite, epidote and, less frequently, almandite.

Sills

The greenish to dark gray sills are very fine-grained (0.05–0.4 mm) rocks covering in composition the same range as their hosts. The texture is usually allotriomorphic-granular, less common, particularily at the chilled margins, it is porphyritic to microporphyritic. They consist of hornblende, plagioclase and quartz in variable proportions. Clinopyroxenes are less frequent but a former occurrence in significant amounts especially as phenocrysts is suggested. The modal amount of hornblende decreases from 40% in the basic sills to less than 2% in the acidic ones. Accessory biotite is present in some intermediate and acidic sills, where it is largely replaced by chlorite. The type of phenocrysts changes from pyroxene and hornblende in the basic to plagioclase in the acidic sills. Plagioclase and quartz appear as micrographic or myrmekitic intergrowths in the mesostasis already at 56% SiO_2.

Volcanics

The volcanic rocks from Sithonia are either pillowed lavas or massive, mostly andesitic flows. The pillowed lavas show fine-grained, slightly porphyritic to glomeroporphyritic textures. They consist of green hornblende and plagioclase with variable proportions of quartz. The grain size ranges from 0.01–0.05 mm. The phenocrysts are mostly plagioclase (0.6–1 mm), less common hornblende. The abundant 5 mm measuring vesicles are filled with either epidote rimmed by quartz or with a mixture of epidote, quartz, and chlorite, less commonly quartz and calcite. The massive andesitic flows consist of 0.5 cm large, subhedral phenocrysts of zoned plagioclase in a fine-grained groundmass (0.2 mm) of lath-shaped plagioclase and minor hornblende.

The volcanics are mostly altered into greenschist with one of the following parageneses:

albite + chlorite + epidote + calcite
albite + chlorite + epidote + actinolite.

These assemblages are attributed to subsea-floor hydrothermal metamorphism and suggest a high geothermal gradient. The minor sulfide mineralization (mainly pyrite) is obviously the result of this alteration.

Petrochemistry

Major and Minor Elements

Harker variation diagrams for the major and minor elements are given in Figs. 3 and 4. The K_2O content averages 0.22% and is plotted against SiO_2 in a separate diagram (Fig. 7).

The gabbroic to pyroxenitic xenoliths included within the Chortiatis suite are plotted in the ruled area. The significance of these xenoliths lies in the possibility that they may represent relics of the magma source. For comparison, the field of the Thessaloniki gabbronorites is also shown. As can be seen from Figs. 3 and 4, the Chortiatis rocks just match the gabbronorite fields. However, each of these lithologies follows its own trend. Where the gabbronorites evolved mainly towards Fe- and Ti-enrichment with simultaneous decrease of silica thus defining a tholeiitic trend, the Chortiatis rocks display a trend of Na- and Si-enrichment.

Two points will be discussed in more detail:

1) The sills cover the same compositional range as their coarser-grained hosts, the main difference is solely textural. The identical chemistry of both rock types indicates that neither is parental to the other.

Firstly, the sills are less siliceous than the rocks they immediately intrude and consequently they cannot be regarded as the more evolved filter-pressed liquid of a differentiated magma. The derivative nature is suggested for the discordant dyke with the highest SiO_2 content of 81.5 wt.%, so far recorded.

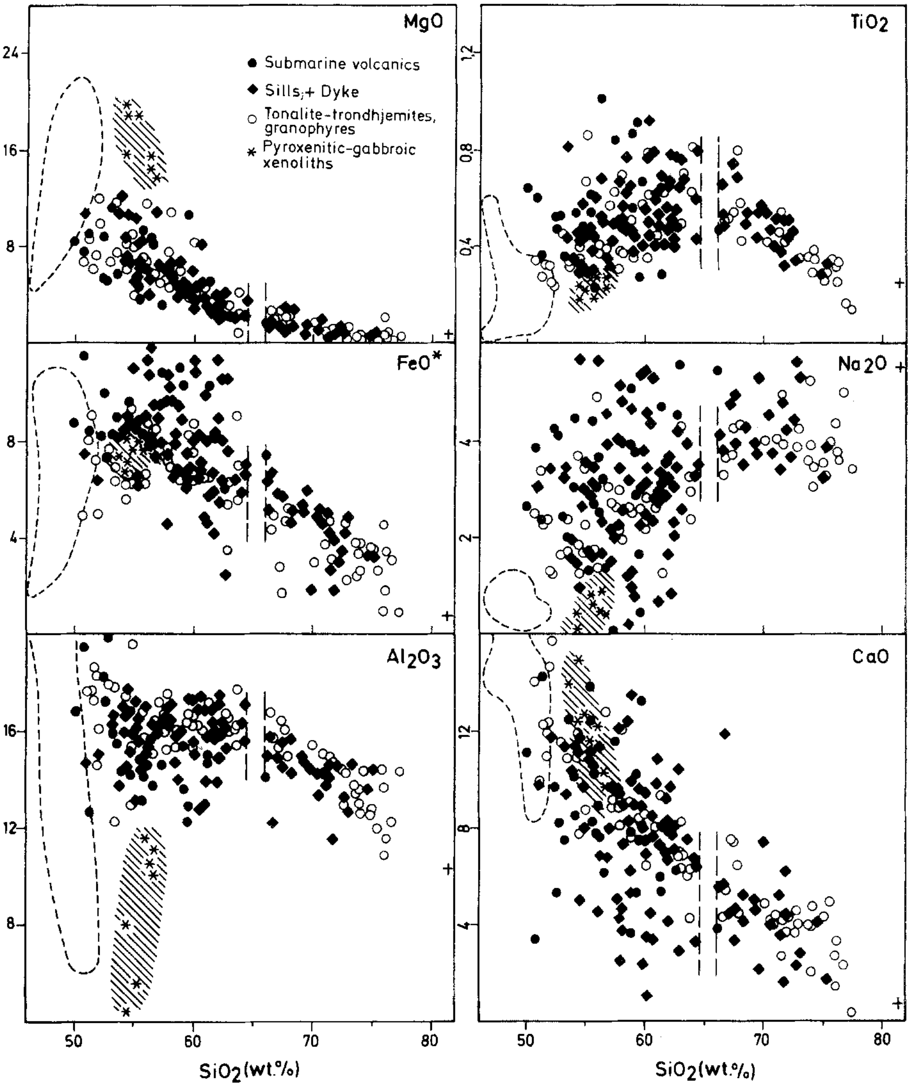

Fig. 3. Harker variation diagrams of the major elements oxides for the Chortiatis magmatic suite. Dashed area: gabbronorite field of Thessaloniki ophiolite; ruled area: field of assumed source rocks; vertical dashed lines refer to the silica gap

Secondly, on a broad-scale there is for every sill a corresponding coarser-grained rock with the same chemistry. This reasoning precludes the possibility that the sills were solidified from a less differentiated melt parental to their hosts.

2) A compositional gap exists between 64.5 and 66 wt.% SiO_2 on water-free base, corresponding to 62.6–65 wt.% SiO_2 of the original data. This gap separates the gabbro-tonalite from the trondhjemite group. Both groups differ

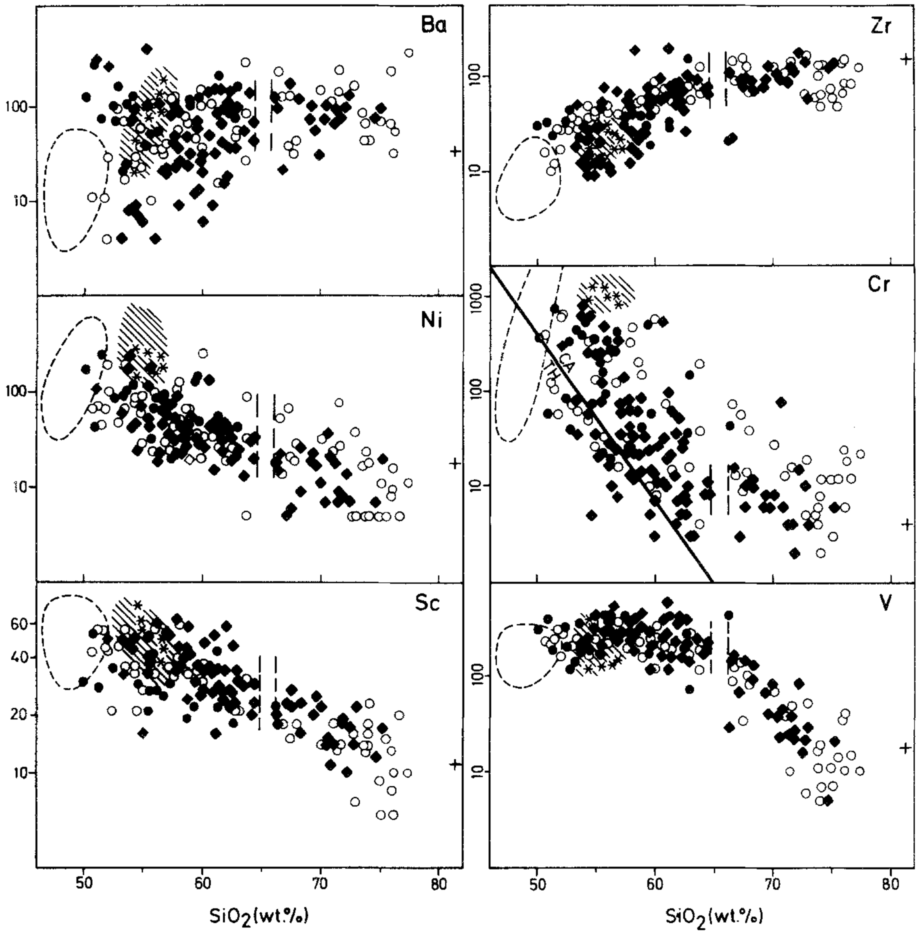

Fig. 4. The same as in Fig. 4 but for the minor elements (logarithmic). The trend in the Cr-SiO_2 plot is after Miyashiro and Shido (1975)

markedly in the behaviour of some major and minor elements with increasing silica. For both groups Al_2O_3, FeO*, MgO, and CaO decrease with increasing SiO_2 content. The same applies also for the refractory elements Ni, Sc, Cr, and V. However, the rate of this decrease is different for both groups.

The most spectacular feature is the variation of TiO_2 and V. In the gabbroic-tonalitic group, TiO_2 increases with SiO_2, meanwhile V remains almost constant. This group is characterized by higher average contents of Cr, Ni, and Sc. In the trondhjemitic group, both TiO_2 and V markedly decrease with increasing silica. It may be argued that the decrease of Ti and V contents is due to their removal by magnetite crystallizing at an early stage. However, the temporal relations of both groups as evidenced by the sills provide convincing arguments that the behaviour of TiO_2 and V as well as the silica gap separating both groups are not simply the result of fractional crystallization: Within a group of sills with known sequence of emplacement, the SiO_2 content abruptly falls from the one to the next following sill generation. The difference in this content between two successive sill generations is as large as 7–15 wt.%. The general rule is that the last-formed and youngest sills are the most basic. The same probably applies to the host rocks of the sills, which in view of the irregular variation of their chemistry up sequence may have also crystallized from several independent melts. These relations cannot be reconciled with progressive fractional crystallization but are rather suggestive of multistage fractional melting.

Partial melting models of a basaltic, amphibolitic or eclogitic source were also proposed for the formation of some trondhjemites by several authors (Arth and Hanson 1972; Hanson and Goldich 1972; Hietanen 1975; Payne and Strong 1979). For others, especially those showing a complete range in composition from gabbro to trondhjemite, a fractional crysstallization model was rather assumed (Hietanen 1943, 1975; Arth and Barker 1976).

The silica gap between the intermediate and acidic Chortiatis rock groups may be the result of one or more of the following processes: a) Temporary equilibrium melting; b) increase in the degree of partial melting; and c) incorporation of a new phase in the melting process.

Post-igneous Modifications and Reasons of K-deficieny

Broadly speaking, the Chortiatis magmatic suite is characterized as being K_2O-deficient, Na_2O-dominant. Aside from both oxides, the contents of CaO and MgO are generally higher than in other siliceous rocks at equivalent SiO_2 contents. During regional and hydrothermal greenschist metamorphism, these four oxides behave differently. Bischoff and Dickson (1975) demonstrated that K_2O and CaO are extracted from basalt during its reaction with sea-water whereas MgO, and possibly also Na_2O become more concentrated. The high Na_2O content in the Chortiatis rocks may be in part the result of post-igneous changes. As shown in Fig. 3, this content varies with increasing silica along an almost vertical line in the tonalitic group, whereas in the trondhjemitic group the Na_2O variations define a flat trend parallel to the SiO_2 axis. Thus, some intermediate rocks are as Na_2O-rich as the most acidic ones. The petrographic examination does not rule out the possibility that some intergrowths of plagioclase and quartz are metasomatic in origin resulting from the introduction of Na_2O. As regards MgO, the concomitant enrichment in the immobile ferromagnesian elements Ni, Cr, and V strongly suggests that MgO was not markedly influenced by later metamorphic processes. This assumption is substantiated by the significant correlation of this oxide with silica. At the other hand, the depletion of the Chortiatis rocks in K_2O entails a serious problem concerning its origin, not only because of the mobility of this oxide but also in view of the simultaneous depletion in the chemically related, mobile elements Rb, Sr, and Ba. This depletion can be easily explained as due to secondary leaching of the K-group elements by waters (e.g. Coleman 1977). However, several lines of evidence indicate that this process has played only a minor role in the chemical modification of the investigated rocks. The most important criteria in support of this conclusion are listed below.

Geological criteria:

1) Volcanics and sills are as K_2O-poor as the coarser-grained trondhjemites and granophyres despite contrasted textures that would govern the penetration of water through them and consequently the extent of K_2O-removal.

2) Prior to the tilting of the Chortiatis magmatic suite, water has to percolate with the same efficiency through a heterogeneous rock pile for a depth of at least 5 km to account for the low K_2O contents throughout the whole stratigraphic sequence of this suite.

3) The consistently low K_2O content both along and across the strike of the Chortiatis rocks is in marked contrast with the otherwise differential behaviour of K_2O in some geographically related acidic rocks during their hydrothermal alteration. The granodiorite that has intruded the Chortiatis rocks along their tectonic boundary with the Sithonia ophiolite displays selective extraction of K_2O at the one site and its redeposition at another site. In these cases, the K_2O-removal is compensated by the introduction of Na_2O, so that the total alkali content does not markedly change.

Petrographical criteria:

1) The plagioclase commonly displays growth zoning. A later formation at the expense of former K-feldspars can be, therefore, excluded. The gneiss xenoliths enclosed within the Chortiatis suite and which experienced the same post-igneous alteration as this suite have completely retained their potash feldspars. Furthermore, authigenic formation of microcline in appreciable amounts has even occurred in some sandstone xenoliths.

2) There is no apparent relation between the extent of alteration and the K_2O content. In some most fresh intermediate rocks with green hornblende and zoned plagioclase this content is as low as 0.03%.

3) Aside from biotite, there is no evidence of a primary occurrence of other K-minerals. The modal proportion of biotite does not have initially exceeded 2–3%, so that this mineral would contribute with at best 0.2% K_2O to the whole rock. An additional but less significant amount of K_2O is incorporated in plagioclase and hornblende. The microprobe analyses of non-altered grains of both minerals show them to contain up to 0.17 and 0.5% K_2O respectively.

The accessory biotite is mostly converted into chlorite, thus providing the opportunity for K_2O to migrate. Another possibility of K_2O-removal is the widespread replacement of basic to intermediate plagioclase by epidote.

The above criteria strongly suggest that the K-deficiency of the Chortiatis rocks dates back to the magmatic stage and that it was merely intensified through post-igneous changes. This deficiency is believed to be either inherited from the source or it was later introduced into the parental melt. According to Collerson and Fryer (1978), carbonic fluids rich in oxidized S and halogenes are capable for complexing and transporting K, Rb, heavy REE's and possibly also Sr and Ba from the magma. The geological relations at Chalkidiki fulfill most of the requirements of this model. The large amounts of Triassic limestones may have provided a continuous influx of CO_2. Sulfur must have been available in significant amounts as suggested by the striking abundance of pyrite in this area.

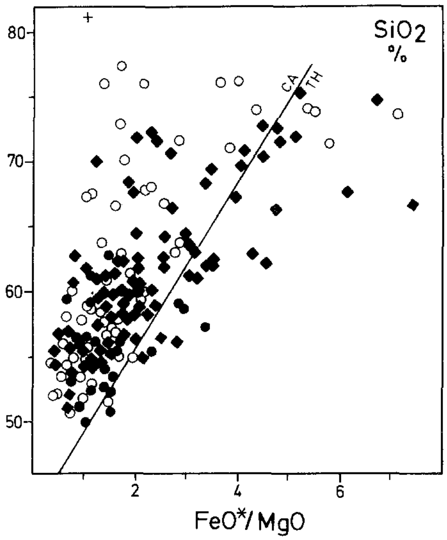

Fig. 5. Variation of SiO_2 with FeO^+/MgO (after Miyashiro 1975). FeO^+ means total Fe as FeO. Same symbols as in Fig. 3

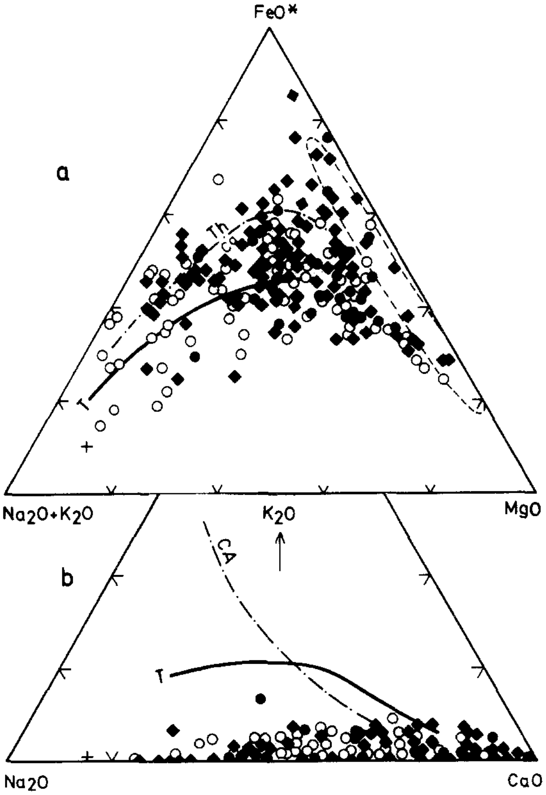

Fig. 6. AFM and K_2O-CaO-Na_2O diagrams for the Chortiatis rocks. The tholeiitic trend after Irvine and Baragar (1971); the trondhjemitic and calc-alkalic trends after Barker and Arth (1976)

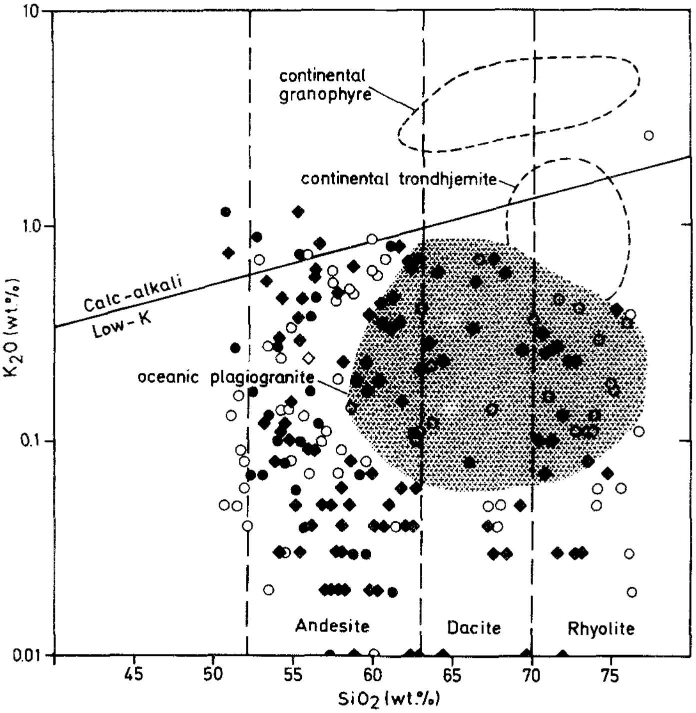

Fig. 7. Log K_2O versus SiO_2 diagram for the Chortiatis suite. The fields of continental granophyre and trondhjemite and of oceanic plagiogranite after Coleman (1977); rock classification after Peccerillo and Taylor (1976)

Type of Rock Series

The total alkali content has been used by Kuno (1968) and Irvine and Baragar (1971) to discriminate between different volcanic series. In the investigated rocks this content is largely presented by Na_2O. In Fig. 3 there is an irregular increase of Na_2O with increasing silica, but in view of the low K_2O content (average 0.22 wt.%), the rocks classify as tholeiitic according to Kuno's definition. A convenient discrimination may be achieved by using the trace elements or the FeO*/MgO as suggested by Miyashiro (1975) and Miyashiro and Shido (1975). In the SiO_2-Cr diagram (Fig. 4), the majority of the analyzed rocks classify as calc-alkaline and about one fifth as tholeiitic. A similar picture is obtained from the FeO*/MgO versus SiO_2 diagram (Fig. 5). Since the same samples recurrently plot within the tholeiitic field also in other diagrams not shown here, a contribution of a tholeiitic melt is likely. The predominant calc-alkaline character of the Chortiatis rocks is well displayed by the variation of TiO_2 with FeO*/MgO which defines a flat line with increasing FeO*/MgO, strictly following after Miyashiro the calc-alkaline trend.

In the AFM diagram (Fig. 6a), the trend followed by the Chortiatis magmatic suite contrasts markedly with the pronounced tholeiitic trend of the Thessaloniki gabbronorites. According to this figure, the Chortiatis rocks classify also as calc-alkaline. This is not the case when K_2O and Na_2O are plotted separately as shown in Fig. 6b. It can be seen from this figure that the calc-alkaline affinity is essentially due to the distinct enrichment in Na_2O alone instead of in Na_2O and K_2O as it is typical of calc-alkaline series. The Chortiatis rocks differ also from trondhjemites in having still lower K_2O content. This content steadily decreases with increasing Na_2O/CaO ratio and is negligible in the most evolved, Na- and SiO_2-rich pegmatitic dykes. Nevertheless, a significant correlation between SiO_2 and K_2O is not present (Fig. 7). According to the classification of Peccerillo and Taylor (1976) shown in Fig. 7, The Chortiatis rocks correspond to the low-K tholeiites. The distribution of minor elements is also consistent with this character. The Zr/TiO_2 ratio used by Winchester and Floyd (1977) as index of alkalinity is low, averaging 0.005. This ratio varies only slightly with increasing silica following a steep trend similar to that of low-K andesite-rhyodacite volcanic arc series.

Discussion

Relation of the Chortiatis Magmatic Suite to the Associated Ophiolites

The temporal and spatial association of the salic Chortiatis rocks with ophiolites of diverse origins strongly argues for a close genetic-geotectonic relation. Geophysical studies by Makris (1977) reveal a mantle upwelling along the strike of these rock units, where the continental crust thins out locally to 30 km. Laterally, both rock units undergo similar lithological variations. At central Chalkidiki, the Chortiatis magmatic suite is present as hypabyssal tonalites and trondhjemites; the juxtaposed Thessaloniki ophiolite as peridotite, websterite, and gabbronorite. This hypabyssal/plutonic association is replaced by submarine eruptions at Sithonia. Here, granophyres and intermediate volcanics occur instead of trondhjemites, and the associated ophiolite is presented by sheeted dykes and basic volcanics. The conclusion to be made from these covariations is that they are the result of causal variations within a particular tectonic regime.

The plutonic/hypabyssal association of central Chalkidiki is incorporated within older accretionary terranes. There is no evidence for a former existence of oceanic crust in this area. The intrusive relations between the mafic-ultramafic cumulates and the tectonite peridotites of the Thessaloniki ophiolite as well as the absence of sheeted dykes and submarine volcanics have led Mussallam and Jung (1985) to assume a continental setting for it. Recently, these authors (in press) proposed that the Thessaloniki ophiolite may have been emplaced within transtensional zones along a transcurrent fault. However, neither an extensive mylonitization, nor antithetic and synthetic faults that commonly accompany wrench faulting were observed. Jung et al. (1981) have argued that this suite may have evolved from the gabbroic rocks of the Thessaloniki ophiolite. These authors have, however, recognized that the volumetric relations are not consistent with a comagmatic origin. A re-evaluation of the geological data reveals that the Chortiatis magmatic suite unambiguously predates the Thessaloniki ophiolite, thus completely precluding such an origin.

The volcanic/subvolcanic association of southern Chalkidiki was evidently formed in an "oceanic" environment. The presence of sheeted dykes in the

Upper Jurassic Sithonia ophiolite indicates that it was originated above a spreading axis. The ophiolite is now tectonically overlain by the intermediate submarine lavas and granophyres of the Chortiatis magmatic suite. Mussallam and Jung (in press) suggested that this suite has constituted the basement for the spreading that resulted in the formation of the Sithonia ophiolite. The intermediate, commonly offset dykes in the Chortiatis volcanics have like the Sithonia sheeted dykes NE-trends, suggesting that their emplacement may have been influenced by this spreading. Chemically, the dykes are, however, more related to the Chortiatis suite. The sedimentary rocks overlying both this suite and the Sithonia ophiolite display similar style and degree of deformation and partly also similar sedimentary facies. A palaeontological study may reveal whether or not they are of the same age. The spreading direction as judged from the northeastern strike of the sheeted dykes correponds fairly to the transport direction from SE to NW as inferred from the mesoscopic folds and the regional geology (Mussallam and Jung, in press). However, it is almost perpendicular both to the northwestern trend of the Sithonia ophiolite and to the major alpidic structures of Chalkidiki. Opadhyay and Neale (1979) inferred from similar relations in some Newfoundland ophiolites that these ophiolites were generated in marginal basins, where spreading may have taken place disorderly along randomly oriented ridges.

The junction between both terranes is characterized by an autochthonous hypabyssal sequence comprising a "high-level gabbro" and a sill complex (Fig. 1). This sequence occurs there, where the Chortiatis magmatic suite is absent. The high-level gabbro constitutes a fractionated series of gabbronorite to diorite and quartz diorite (Table 1, column 6). It displays complete mineralogical and chemical gradations between the cumulate gabbronorite (Table 1, column 9) of the Thessaloniki ophiolite and the more silicic noncumulates of the Chortiatis suite (Table 1, column 1–5). Another point of similarity is the frequent occurrence of contact-metamorphic sedimentary rocks both in the high-level gabbro and in this suite. The basic to intermediate sill complex is intrusive in a clastic sedimentary succession of unknown age. This succession obviously post-dates the penetratively deformed Middle Jurassic Svoula Flysch. The sill somplex was interpreted by Mussallam and Jung (1985) as the result of incipient spreading which ceased at an embryonic stage. This failed spreading is probably related to the active spreading center of Sithonia. As with the high-level gabbro, the sills overlap in their composition both the ophiolite gabbronorite and the Chortiatis magmatic suite (Table 1, column 7). Their low Ti, Zr, and Y contents, however, clearly point to low-K tholeiites, suggesting an island-arc setting for the hypabyssal sequence.

Probably related to the same spreading process are also the microdioritic dykes which cross-cut the Thessaloniki ophiolite preferably in its southeastern protrusions. The dykes strike NE-SW, mostly following normal faults. They were in situ introduced subsequent to the emplacement of the Thessaloniki ophiolite in response to localized magmatic activity and extensional faulting. The dykes are mostly not altered, having SiO_2 contents up to 60 wt.%. Again, they also correspond to low-K tholeiites. In account of their lower Ce, Zr, and Y concentrations (Table 1, column 8), they are closer to the Chortiatis rocks of

Table 1. *Average Chemical Compositions of the Chortiatis Rocks and Associated Ophiolites*

Column	1	2	3	4	5	6	7	8	9
Analyses	45	59	31	43	47	62	63	80	159
SiO_2	60.20	61.25	63.51	56.87	54.29	51.83	52.85	54.08	47.69
Al_2O_3	14.76	14.65	14.64	14.75	14.24	15.24	14.78	15.01	16.07
Fe_2O_3	1.39	1.74	2.45	3.41	8.89*	1.82	2.86	1.75	1.15
FeO	4.31	4.34	2.92	5.15		6.25	5.72	7.35	6.33
MnO	0.09	0.09	0.09	0.15	0.14	0.15	0.13	0.16	0.15
MgO	5.18	4.39	3.10	4.87	6.00	7.88	5.80	5.84	11.51
CaO	7.97	7.21	6.87	6.67	8.33	11.55	10.22	10.21	14.58
Na_2O	2.91	3.03	3.31	3.06	2.97	1.81	1.48	1.46	0.38
K_2O	0.29	0.29	0.12	0.11	0.23	0.13	0.07	0.16	0.03
TiO_2	0.45	0.51	0.37	0.46	0.49	0.50	0.46	0.50	0.25
P_2O_5	0.06	0.07	0.06	0.04	0.04	0.04	0.03	0.03	0.00
H_2O^+	2.09	1.97	1.70	3.05	3.21	1.90	3.58	2.38	1.20
H_2O^-	0.09	0.09	0.16	0.19		0.22	0.30	0.27	0.16
CO_2	0.09	0.15	0.03	0.53		0.17	1.08	0.31	0.08
SO_3	0.00	0.01	0.06	0.09	0.00	0.07	0.15	0.07	0.09
Minor elements (ppm)									
Ba	83	86	26	10	102	28	72	26	9
Ce	29	31	19	14	14	13	10	9	8
Co	47	44	54	51	–	69	49	70	72
Cr	196	131	67	67	224	219	157	121	403
Cu	32	27	32	67	72	46	70	65	61
Ni	76	54	31	37	71	78	61	50	122
Pb	3	3	6	6	12	6	6	7	5
Rb	6	7	4	4	12	8	4	7	3
Sc	31	28	28	44	27	47	49	52	56
Sr	161	211	134	94	84	164	117	88	57
Th	1	5	4	6	–	5	4	7	3
V	175	166	122	267	274	301	324	300	257
Y	11	16	27	19	16	15	16	16	5
Zn	25	22	29	68	63	55	52	65	41
Zr	71	73	57	30	30	26	18	20	5
La	21	32	18	12	14	20	24	16	8
Nb	1	1	7	6	5	4	3	3	3

FeO* means total iron as Fe_2O_3

1–2: Chortiatis rocks from central Chalkidiki; 1 = tonalite-trondhjemite; 2 = sills.

3–5: Chortiatis rocks from Sithonia; 3 = granophyres; 4 = sills; 5 = volcanics.

6–7: Hypabyssal sequence at Metamorphosis; 6 = "high-level gabbro"; 7 = sill complex.

8: Microdioritic dykes; 9 = gabbronorite.

Sithonia (Table 1, column 3–5). Thus, the generation of low-K tholeiitic magmas was not only restricted to the Middle Jurassic Chortiatis rocks.

Comparison with Trondhjemites

Mineralogically and petrographically, the Chortiatis magmatic suite corresponds to other tonalite-trondhjemite series and granophyres. Association with geosynclinal sediments, ultramafic rocks and later granitic intrusions is typical for most trondhjemites (Hotz 1971; Phelps 1979). Some trondhjemites, especially those of Archaean age are also interlayered with dark, fine-grained sills (McGregor 1979), thus resembling in their appearance the Chortiatis magmatic suite except for the intermediate and acidic compositions of the sills in the latter. In others, dykes instead of sills are present (Phelps 1979). Phanaerozoic trondhjemites occur according to Barker et al. (1976) and Barker (1979) at compressional plate margins which represent junctions between oceanic-oceanic or oceanic-continental plates and are almost certainly related to subduction. Several authors suggested that Na-dominant trondhjemites are followed by potassic granites within a particular igneous cycle (e.g. Collerson and Fryer 1978). Hotz (1971) proposed a model to explain this association in the western United States by assuming a subducted oceanic slab dipping toward the potassic granites.

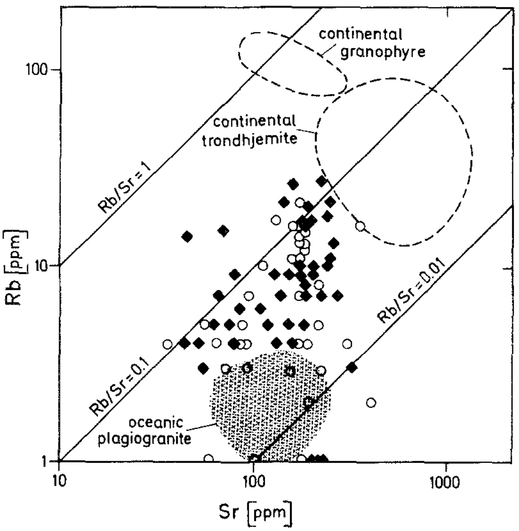

Fig. 8. Log Rb versus log Sr diagram for the Chortiatis rocks. Fields after Coleman (1977)

Among the Mesozoic and Tertiary granitic to monzodioritic intrusions of Chalkidiki, that at Arnaea (Fig. 1) is probably related to the Chortiatis magmatic suite. This intrusion is situated near the western margin of the Serbomacedonian Massif and extends parallel to the trondhjemites of central Chalkidiki. Radiometring dating of the Arnaea granite is still not available but field relations indicate a Jurassic age.

Despite the strong geological and petrographical similarities, some crucial chemical differences are present. In Fig. 6a, the Chortiatis rocks plot mostly inbetween the tholeiite-calcalkaline discriminant and the trondhjemite trend, and in Fig. 6b they are shifted toward the Na-Ca join. Indeed, the trend displayed by the Chortiatis rocks in Fig. 6b sets them apart from known rock series and for the first glance this unique behavior appears to be solely due to their K_2O-deficiency. The higher contents of CaO, MgO, and to a less extent Na_2O in the Chortiatis rocks are one possible reason. Available data on minor element abundances in other trondhjemites are not sufficient to elucidate these differences and to highlight their meaning. In general, the Chortiatis rocks contain higher amounts of Ce, La, Ti, Zr, and Ni and lower of Sr and Rb. In Fig. 8 they fall mostly within the gap separating continental and oceanic trondhjemites with an apparent affinity to the latter (see also Fig. 7). Their Rb/Sr ratio averages 0.034 and is much closer to mantle values (0.02–0.03) than those of the upper continental crust (0.25–0.35).

Palaeotectonic Setting

The mineralogical and chemical similarity between the tonalitic-trondhjemitic rocks and the later introduced sills suggests that the parental magma has, if ever, experienced only a minor differentiation. This assumption is supported by the rarity of a phenocryst phase and by the absence of significant and coherent chemical variations between the middle parts and the chilled margins of the sills. A formation by multi-staged fractional melting is suggested for the Chortiatis magmatic suite. Uncertainties, and differing views of the two authors, arise as regards the source region, the conditions of partial melting and the trigger mechanism for magmatic activity. One of us (K.M.) prefers subduction from West to East; there is good geological support for this view. The other (D.J.) considers mobilization of continental granulitic lower crust and/or uppermost subcontinental mantle due to crustal thinning prior to rifting a possibility which should be examined. The following points can be used to support the subduction model: Wyllie (1979) demonstrated that melting of mafic granulite expected to occur at 1100 °C produces trondhjemitic and tonalitic melts. In account of this high temperature, he concluded that these melts "cannot be generated by anatexis of the continental crust under conditions of normal regional metamorphism and that these magmas may represent crystal mushes unless there is a significant contribution of heat and material from less siliceous magmas" generated from subducted oceanic crust. Most authors relate the trondhjemites, therefore, to subduction zones (e.g. Hotz 1971; Hietanen 1975; Barker et al. 1976; Phelps 1979), where low-temperature partial melting of wet eclogite or amphibolite of basaltic composition at mantle depths yields the required magmas (Green and Ringwood 1968).

Indeed, the polarity of the stratigraphical, structural and magmatic facies discussed earlier, the parallelism of these facies to the margin of the Serbomacedonian Massif and the apparent increase of deformation and metamorphic grade toward this Massif are all suggestive of an active continental margin. The occurrence of Palaeozoic and Mesozoic ophiolite respectively within or near the margin of the Serbomacedonian Massif is consistent with this suggestion.

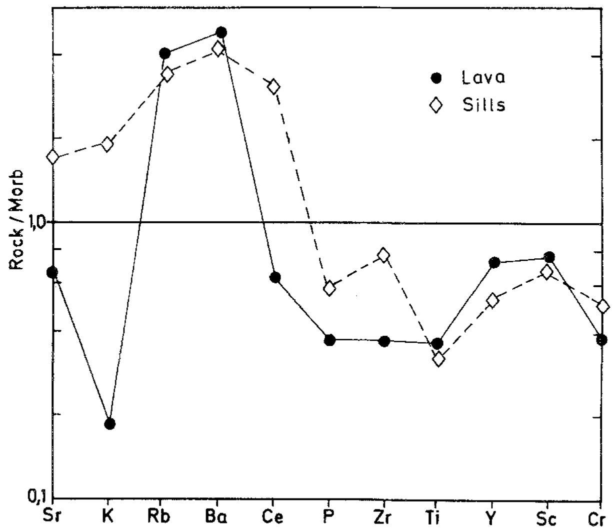

Fig. 9. Trace element patterns for the Chortiatis lava from Sithonia and for the sills of central Chalkidiki (after Pearce et al. 1981)

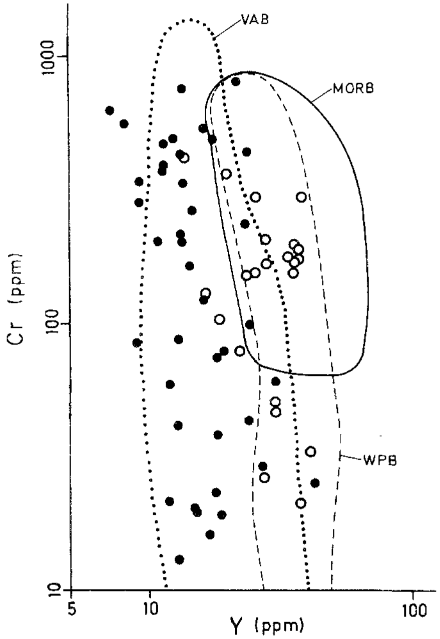

Fig. 10. Cr-Y diagram for the submarine volcanics of the Chortiatis magmatic suite and of the Sithonia ophiolite (after Pearce et al. 1981). See Fig. 11 for key

The direct and most compelling evidence is provided by the chemistry of the Chortiatis lavas at Sithonia. Fig. 9 shows the geochemical pattern for a very fresh fine grained dioritic lava (55.7% SiO_2) with plagioclase and hornblende as the main constituents. Except for Cr, which is enriched in some samples (compare Fig. 10), this pattern holds also for other lavas analysed. The main differences lie in the extent of depletion or enrichment. The Chortiatis pattern strongly resembles that given by Pearce et al. (1981) for volcanic arc tholeiites, but it differs from the latter in the marked Sr and K depletion. However, in some more siliceous lavas either of both elements is as abundant as in MORB. In the Cr-Y diagram (Fig. 10), the Chortiatis lavas plot within the volcanic arc field. The large variations in the absolute abundance of Cr in this figure is less dependent on the silica content. In Fig. 11 the lavas fall also in the volcanic arc field with the more basic ones extending to still lower Ti and Zr contents. Within the recorded silica range of 50.0–66.1 wt.% for these lavas, both elements increase with increasing SiO_2 along almost parallel lines (Figs. 3 and 4). These data point at an island-arc setting for at least the Chortiatis magmatic suite of Sithonia. This conclusion is substantiated by the chemistry of the adjacent Sithonia ophiolite. In Figs. 10 and 11, the ophiolite lavas are also plotted. In Fig. 10, about 60% of these lavas fall within the MORB field, the others within the volcanic arc field. In Fig. 11, this discrimination is still obvious. A similar picture is also obtained from Ti-Cr and Ti-Zr-Y diagrams (Jung and Mussallam 1985). Ophiolites that display characteristics both of MORB and of volcanic arc are interpreted by Pearce et al. (in press) to have originated by back-arc spreading following arc volcanism. The abundance of intermediate, partly brecciated lava flows and the occurrence of large volumes of rhyolite in the Sithonia ophiolite are consistent with a back-arc origin.

These two different lines of evidence strongly argue for a volcanic arc setting. The facies distribution and age relations point at a NE-dipping subduction during the Middle Jurassic. The oceanic crust to be subducted is supposed to have lain one to a few hundred km to the west, presumably within the present Subpelagonian zone. Evidence for the existence of a vanished ocean in this zone is supplied by the occurrence of several ophiolite complexes (e.g. Vourinos, Othris). Destruction of this ocean and the ophiolite emplacement were related to an E-dipping subduction in Jurassic time (Smith and Spray 1984).

An island-arc setting must be also envisaged for the hypabyssal Chortiatis trondhjemites of central Chalkidiki which present the lateral continuation and chemical equivalents of the granophyres and submarine volcanics at Sithonia. These trondhjemites as well as their associated sills would similarily plot within the volcanic arc fields in Figs. 10 and 11. For comparison, the average minor element abundances in the sills from central Chalkidiki are given in Fig. 9. The most distinctive property of the rocks from this area is the markedly higher concentration of Ce. In addition, both the trondhjemites and the sills are generally more enriched in Sr and K and less depleted especially in P and Zr than their counterparts at Sithonia. Both features point at a slightly higher alkalinity of the Chortiatis rocks in central Chalkidiki. Nevertheless, these rocks still classify as low-K tholeiites. Recently, Schünemann (1985) has studied the Chortiatis trondhjemites in detail and suggested, as did Jung et al. (1981) that they are

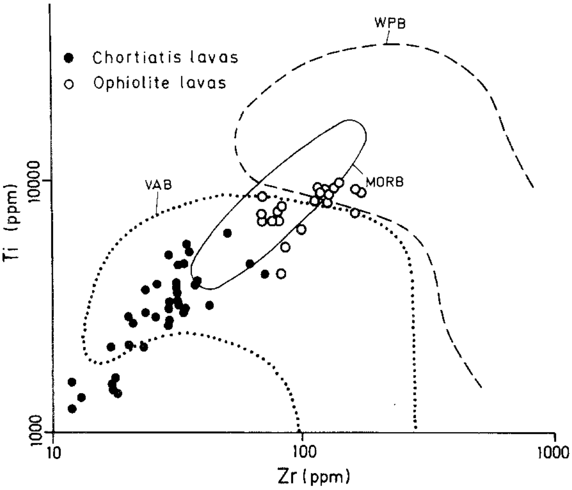

Fig. 11. Ti-Zr discrimination diagram for the submarine Chortiatis and ophiolite volcanics from Sithonia (after Pearce et al. 1981)

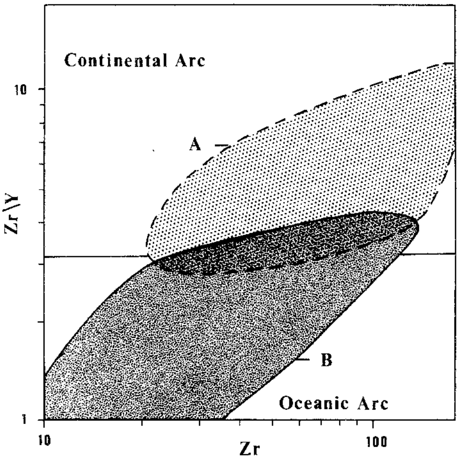

Fig. 12. Plot of Zr/Y versus Zr for the Chortiatis rocks (after Pearce, in press). *A* Central Chalkidiki (mainly sills), *B* Sithonia (mainly volcanics and sills)

calc-alkaline owing their K-deficiency to secondary processes. Though the present authors cannot share this view, Schünemann's assumption that the trondhjemites may present the plutonic member of an island arc is appreciated. Relative to the granophyres and submarine volcanics of Sithonia, the trondhjemites and sills of central Chalkidiki have higher Zr/Y ratios and higher Zr contents (Fig. 12), suggesting, according to Pearce (in press), a continental arc setting. Such a setting is consistent with the occurrence of subaerial eruptions and with the geological relations. The oceanic arc setting of the Chortiatis rocks at Sithonia does not imply that they were formed on an older oceanic crust.

Though the basaltic intercalations in the adjacent Svoula flysch display clear affinities to MORB, there is no evidence for the existence of an oceanic crust preceding the Chortiatis rocks in this area. Secondly, the Chortiatis rocks have, with certainty, been formed subsequent to the pervasive deformation and uplift of the flysch. The lateral variations in lithology and in solidification depth of the Chortiatis magmatic suite can rather be attributed to progressive attentuation of the continental crust in SE direction, as demonstrated by Makris (1977) and substantiated by the initiation of spreading in southern Chalkidiki. This attenuation has apparently also fascilitated the formation of sills instead of extensional dykes.

Acknowledgements

We are thankful to Prof. Dr. W. Johannes, Dr. F. Kockel, and Prof. Dr. E. F. Stumpfl for critically reading the manuscript and for their constructive comments and linguistic improvements. The XRF analyses were carried out at the Bundesanstalt für Geowissenschaften und Rohstoffe (Hannover) and at the Mineralogisch-Petrographisches Institut (Hamburg). For this facility we are indebted to Prof. Dr. F.-J. Eckhardt, Dr. H. Raschka, Mrs. Lodziak and Requard (all at Hannover) and to W. Vogel (Hamburg). Dr. H. Kreuzer (Hannover) has kindly supplied the radiometric data. This work was partly financed by the Deutsche Forschungsgemeinschaft (Bonn).

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