Investigation of the mineralogical petrographic, geochemical and physical properties of carbonate rocks from Ileia Prefecture and assessment for industrial applications

Tseni X. University of Patras, Department of Geology, Section of Earth Materials
Koutsopoulou E. University of Patras, Department of Geology, Section of Earth Materials
Tsikouras B. University of Patras, Department of Geology, Section of Earth Materials
Hatzipanagiotou K. University of Patras, Department of Geology, Section of Earth Materials

To cite this article:

INVESTIGATION OF THE MINERALOGICAL, PETROGRAPHIC, GEOCHEMICAL AND PHYSICAL PROPERTIES OF CARBONATE ROCKS FROM ILEIA PREFECTURE AND ASSESMENT FOR INDUSTRIAL APPLICATIONS

Tseni X., Koutsopoulou, E., Tsikouras B., Hatzianagiotou K.

1University of Patras, Department of Geology, Section of Earth Materials, 265 00 Patras, Greece

tseni@upatras.gr, ekoutsop@upatras.gr, v.tsikouras@upatras.gr, k.hatzianagiotou@upatras.gr

ABSTRACT

Research on carbonate rocks has been increasingly important during the last few decades, due to their numerous applications. In this paper, we examined the properties of Cretaceous carbonate rocks from the Olonos-Pindos Zone from Ileia Prefecture. The relationships between various physical properties and between petrographic features and physical properties were defined. This may lead to preliminary evaluation of carbonate rocks using microscopic investigation, which unlike the elaboration of a series of physical and mechanical properties, is a fast and inexpensive method. In addition, these properties, along with their geochemical characteristics, were used to assess the suitability of these carbonate rocks as fillers in various applications. Detailed petrographic study of the collected samples revealed the occurrence of biomicrite, intramicrite (mudstone and wackestone), biosparite (packstones and grainstones), intrasparite and rudstone. From the lower to the upper members, a decrease of the grain size of calcite is observed. X-ray diffraction study of the insoluble residue revealed the presence of quartz, chlorite, illite, smectite, and mixed layer illite-chlorite. The colour index of the investigated powdered samples is negatively influenced by the increase of organic and insoluble residue contents. The water absorption is inversely correlated with CaO content while moisture is positively correlated with insoluble residue. The grainstone and rudstone are characterized as ultra-high pure calcium limestones, except for Mg-rich crystalline dolomitic limestones. The packstones are calcium limestones of high to medium purity. Mudstones and wackestones are characterized as low calcium limestones. The results suggest that all the examined lithotypes can be used as soil conditioners and animal feed supplements; however only grainstones and rudstones are suitable for desulphurization of exhaust gasses and cement production.

Key Words: limestone, physical properties, Pindos Zone, Peloponnesus
Περίληψη

Η έρευνα των ανθρακικών πετρωμάτων σε παγκόσμια κλίμακα παρουσιάζει τις τελευταίες δεκαετίες αυξανόμενους ρυθμούς, γιατί παρέχουν πληροφορίες για την εξέλιξη της τοπογραφίας και τις συνθήκες που επικρατούσαν στην επιφάνεια της Γης κατά τη γέννησή τους και επειδή μπορούν να αποτελέσουν εξαιρετική πρώτη ύλη σε πολλά βιομηχανικά εφαρμογές. Επιπλέον παίζουν σημαντικό ρόλο στη γεωλογία πετρελαίου ως μητρικά πετρώματα και ταμιευτήρες (Tissot and Velte, 1984). Στη εργασία αυτή εξετάζεται η δυνατότητα αξιοποίησης των ανθρακικών πετρωμάτων του Ν. Ηλείας ως πληρωτικών υλικών. Τα δείγματα των ανθρακικών πετρωμάτων ελήφθησαν από τη γεωτεκτονική Ζώνη Ωλονού-Πίνδου, είναι Κρητικάς ηλικίας και αντιπροσωπεύουν, με βάση την ορυκτολογική τους σύσταση, από ασβεστόλιθους και δολομιτικούς ασβεστόλιθους. Ιδιαίτερα προσοχή δόθηκε στη συσχέτιση των ορυκτοπετρογραφικών με τις φυσικές ιδιότητες, με σκοπό να εκτιμηθεί η ποιότητα των ασβεστόλιθων με βάση την μικροκοπική τους εξέταση, η οποία είναι απλή και μη δαπανηρή μέθοδος σε σύγκριση με την εκπόνηση δοκιμών φυσικών ιδιοτήτων. Τα δείγματα εξετάστηκαν σε πολωτικό μικροσκόπιο και έγινε παρατήρηση των ιστολογικών χαρακτηριστικών τους, του μεγέθους των κόκκων τους και της ορυκτολογικής τους σύστασης. Η ταξινόμηση τους έγινε σύμφωνα με τα συστήματα ταξινόμησης των Folk (1959, 1962) και Dunham (1962) και βρέθηκε ότι τα δείγματα που συλλέχθηκαν είναι βιομικρίτες, ενδομικρίτες (mudstone και wackestone), βιοσπαρίτες (packstones και grainstones), ενδοσπαρίτες και rudstone. Επίσης υπολογίστηκε το αδιάλυτο υπόλειμμα, το οποίο στη συνέχεια εξετάστηκε με τη μέθοδο της περιθλασιμετρίας ακτίνων Χ. Από την ανάλυση των περιθλασιογραμμάτων προέκυψε ότι σε αυτό το μη ανθρακικό υλικό συμμετέχουν χαλκαί, αλκαλικοί άστριοι, χλωρίτης, ιλλίτης, βερμικουλίτης, σμεκτίτης και άργιλοι με μικτή δομή ιλλίτη-χλωρίτη. Επιπρόσθετα, σε σκόνες των δειγμάτων προσδιορίστηκαν οι δείκτες χρώματος, με το δείκτη λευκότητα να κυμαίνεται από 78 έως 95. Επιπλέον στα δείγματα προσδιορίστηκε και η συμμετοχή του οργανικού υλικού και φαίνεται ότι πρόκειται για ασβεστόλιθους χαμηλής περιεκτικότητας σε οργανικό υλικό. Η λευκότητα των υλικών επηρεάζεται αρνητικά από την παρουσία του οργανικού υλικού και των οξειδίων του Fe, καθώς η παρουσία τους συμβάλλει στην υποβάθμιση της ποιότητας τους. Με αύξηση του περιεχομένου ασβεστίου μειώνεται η υδαταπορροφητικότητα, ενώ η περιεχόμενη υγρασία συσχέτιζεται θετικά με το αδιάλυτο υπόλειμμα. Επίσης, υπολογίστηκε η χημική σύσταση των ασβεστόλιθων που συλλέχθηκαν. Με βάση την περιεκτικότητά τους σε CaCO₃, οι rudstone και οι grainstones χαρακτηρίζονται ως υλικά υψηλής καθαρότητας, με εξαίρεση το δολομιτικό ασβεστόλιθο, οι packstones ταξινομούνται ως υλικά υψηλής καθαρότητας και τα mudstone και wackestone αποτελούν πετρώματα χαμηλής καθαρότητας. Γενικά τα δείγματα στα οποία κυριαρχούν σπαριτικοί κρύσταλλοι εμφανίζουν υψηλότερη καθαρότητα καθώς και θετικότερη ποιότητα σε σύγκριση με αυτά στα οποία κυριαρχεί μικριτικό υλικό. Τέλος, πραγματοποιήθηκε συγκριτική μελέτη των εργαστηριακών αποτελεσμάτων με σκοπό να διαπιστωθούν οι σχέσεις μεταξύ των φυσικών ιδιοτήτων των ασβεστόλιθων και τις στατιστικές παραμέτρους, καθώς και να διερευνηθεί αν πληρούν προδιαγραφές για την αξιοποίησή τους σε βιομηχανικές εφαρμογές. Η στατιστική ανάλυση των φυσικών ιδιοτήτων των ασβεστόλιθων με απλή γραμμική παλινδρόμηση έδειξε πολύ καλούς έως εξαιρετικούς συσχετισμούς. Τέλος...
προέκυψε ότι όλοι οι λιθότυποι που εξετάστηκαν μπορούν να χρησιμοποιηθούν ως εδαφοβελτιωτικά (διότι περιέχουν Mg<5%), και είναι κατάλληλοι για χρήση ως συμπληρώματα ζωικών τροφών, ενώ μόνο οι grainstone και οι rudstone είναι κατάλληλοι για παραγωγή τσιμέντου και για περιβαλλοντικές εφαρμογές όπως η αποθέωση των καυσαερίων.

**Lέξεις Κλειδία:** Ασβεστόλιθοι, Ζώνη Πίνδου, Φυσικές Ιδιότητες, Πελοπόννησος

1. **Introduction**

Limestones are industrial rocks which are mainly used as crushed rocks for construction purposes, as dimension stones and fillers in concrete, and as road aggregates. Generally, limestone can be used in cement when the Mg content is below 5%, because high Mg contents causes expansion after setting, hence reducing its strength. Ground limestone is widely used to raise the pH of acid soils, as well as an additive in fertilizers and animal foodstuffs. Large amounts of limestone are used in blast furnaces as slag conditioners and in the steel production to form slag; however the large amounts of energy that required to decompose limestone to lime generally limits its use. Limestone is widely used as a fluxing agent in smelting of metals, as well as in bauxite processing and production of alumina. The most widespread use of limestone is the production of quicklime.

Petrophysical properties of sedimentary rocks are influenced by size, shape, and packing of grains, porosity, cement and matrix content, all controlled strongly by depositional fabric and postdepositional processes. This paper aims at investigating the physical properties of Cretaceous limestones from the Pindos Zone of Ileia Prefecture, in order to establish their inter-relationships, to study the relationships of physical properties with their petrographic characteristics and to evaluate their suitability as industrial rocks in various applications. These limestones are the most abundant in the investigated area occupying approximately 72 km², including a large variety of different lithotypes. They are also of potential industrial interest; hence study of their physical properties is important.

**Geological setting**

The geological setting of the Ileia Prefecture, west Peloponnesus, is characterized by the presence of the Ionian, the Gavrovo-Tripolitza and the Olympos-Pindos geotectonic Zones. During the Mesozoic, the Ionian zone corresponded to a vast, intra-platform rift basin bounded on both sides by shallow platforms (Katsikatsos 1992). The early shallow character, of the Ionian basin, during the pre-rift period, is reflected on its older rocks, which include the Permian-Triassic evaporites and dolomites and the neritic Pantokrator limestones of Upper Triassic age, extending mainly to the west part of the study area. During the Lower Jurassic – Upper Jurassic rift period, the Lower siliceous shales with Posidonomya, the red-blue limestones with ammonites (Ammonitico Rosso), the filamentous limestones and the Upper siliceous shales with Posidonomya were deposited (Renz, 1955). The syn-rift formations are overlain by the Upper Jurassic – Lower Cretaceous pelagic Vigla Limestone Formation (Aubouin, 1959; Karakitsios and Koletti, 1992; Karakitsios et al., 2004). The Gavrovo-Tripolitza
Zone includes shallow platform carbonate rocks of Cretaceous-Eocene age, which are covered by vast quantities of detrital sediments (De Wever, 1975; Fleury, 1980). The sedimentary rocks of the Pindos Zone (Fig. 1) originate from an elongate remnant ocean basin that formed during mid-Triassic, consisting typically of deep-water carbonate, siliciclastic and siliceous rocks, ranging in age from Late Triassic to Eocene, covered by thick detrital, late Paleocene to Oligocene flysch sediments (Fleury, 1980; Robertson et al., 1991; Robertson, 1994; Degnan and Robertson, 1998; Degnan and Robertson, 2006).

The lower stratigraphic unit in the Pindos Zone is the Priolithos formation of Katanian age comprising medium-grained sandstone with mudstone intercalations (Fig. 2). Overlying to the Priolithos formation is the Drimos formation composed of turbiditic and hemipelagic limestone. The Lestenna formation overlies the Drimos formation comprising, from bottom to top, the Kastelli mudstone member, mainly composed of multicolored mudstone, the Aroania member, consisting of Jurassic radiolarites and the first flysch, which includes pelites, limestone and sandstone, red mudstone. Subsequently, Lower Cretaceous to Maastrichtian, redepsoited limestone and pelagic limestone were formed. The Kataraktis Passage member overlies this formation, comprising the transition from car-

Fig. 1. Geological map of eastern Ileia Prefecture.

Εικ. 1. Γεωλογικός χάρτης της περιοχής της ανατολικής Ηλείας.
bonate to detrital sedimentation. It includes pure limestone deposition at its base with increasing clastic input towards the top. Finally, the late Palaeocene-early Eocene Pindos flysch lies at the top of the pile, likely extending also to Mid-Eocene age in the SE Peloponnese (Piper, 2006). The investigated Cretaceous carbonate rocks record a transitional time period between major orogenic cycles in the Hellenides (Kafousia et al., 2010). These cycles culminated in the latest Jurassic – Early Cretaceous (Eohellenic phase) and the latest Cretaceous to Tertiary (Meso- and Neohellenic phases) and led to the westerly directed progressive suturing of the Hellenides (Neumann and Zacher, 2004).

**Analytical methods**

Determination of physical properties of

---

**Fig. 2.** Simplified stratigraphic section of the Pindos zone at Ileia Prefecture.  
**Εικ. 2.** Απλοποιημένη στρωματογραφική διάρθρωση της Ζώνης Πίνδου στο Ν. Ηλείας.
the limestones was conducted in the Research Laboratory of Minerals and Rocks, Department of Geology, University of Patras. The insoluble residue was determined after digestion in 25 vol.% acetic acid (Hirst and Nicholas, 1958). The mineralogical composition of the insoluble residue was determined by X-Ray Diffraction (XRD), using a Bruker D8 Advance diffractometer equipped with a LynxEye® detector, at a 3-70° 2θ range with, a scanning step of 0.015° and 0.2 seconds time per step. The diffractograms were evaluated using the EVA v.12 software. The clay mineralogy was determined from three XRD patterns in oriented samples (after air-drying at 250°C, with ethylene glycol treatment, and after heating at 490°C for 2 hours). The organic carbon content was determined with titration according to Walkley and Black (1934) A Hunter color measuring system (Hunter Color Diff. Meter, Miniscan XE plus, Hunter Associates Laboratory Inc., Reston, VA) was used to measure the color. Individual cores were cut transversely and each sample was measured thrice for color values. The information given by L*, a*, and b* is generally expressed as the total color, with L* representing the brightness or dullness, a* for redness to greenness, and b* for yellowness to blueness. The colour properties of the carbonate powder were measured according to the CIELAB system using a Diffusion Systems. The source UV content is nominal match to D65 with port diameters 45/0. The physical properties investigated included moisture content (ASTM D2216), water absorption (ASTM C97-47), bulk specific gravity (AASHTO T100-T85) and apparent specific gravity (AASHTO T147). Three tests were performed for each property and the mean values were recorded. Porosity values (n%) were calculated on rock powders using a pycnometer, according to the ISRM (1981) specification. The total volume of pores is calculated as the difference between the volume of the specimen and that of the powdered particles. Whole rock chemical analyses were performed at Activation Laboratories LTD, Ancaster, Ontario, by fusion ICP-OES for major elements and combined ICP-MS and INAA for trace elements. Detection limit for major elements is 0.01%, except for TiO2 which is 0.005%. Replicate analyses suggest precision better than 5% for major elements and most trace elements. The determination of CO2 was carried out by coulometry.

Results Petrography

Thirty five samples were collected from the Cretaceous limestones and petrographically examined, representing the whole stratigraphic sequence and geographic distribution. The investigated samples were classified after the classification schemes of Dunham (1962) and Folk (1959, 1962). The observed lithotypes include medium-sorted rudstones or oointrabiomicrosparite, which are clast-supported monomict rocks but matrix supported fabric are also detected. Clasts are sub-rounded, mostly composed of micrite and dark oolites (Fig. 3a). Other clasts include reworked limestone containing benthic foraminifera (texturlaria, miliolidae) (Fig. 3b). These samples occur at the slope of the pelagic formations attached to the Gavrovo-Tripolitza Zone. Coarse crystalline, subhedral dolostones contain rhombohedral dolomite grains (Fig. 3c), which frequently display cloudy cores and clear rims (a common feature in replacement dolomite) that have completely obliterated primary fabric and micritic matrix.
These samples are classified as crystalline dolomitic limestones according to Dunham (1962) and as dolocalcitic sparstones according to Wright (1992). Primary and secondary types of porosity were also observed and classified according to the Choquette and Pray (1970) scheme (Fig. 3d). Mudstones or dismicrites contain micritic calcite while mudstones with bioclasts or fossiliferous micrites contain micritic calcite with bioclasts mainly foraminifera (Figs 4a, b). Wackestones or mudstones with bioclasts are composed predominately of micrite matrix that supports sparse bioclast. Radiolarian fauna (Fig. 4d), typically found in Early and mid-Cretaceous, in these wackestones show poor to medium preservation due to reworking and corrosion (Neumann and Zacher 2004). The presence of stylolites is associated with uplift and load release, which commonly leads to separation of the rock fabric along weak surfaces (Figs 3c, 4a, 4c). Sometimes clay rich stylolites (Fig. 4b, 4c) generate elongated and often unconnected secondary porosity zones (Scholle and Ulmer-Scholle, 2003).

**Fig. 3.** Photomicrographs of the studied limestones: (a) Intraclast with oolite in a rudstone (sample DHL 13, plane polarized light); (b) Abundant foraminifera cemented with fine-crystalline calcite (rudstone sample DHL 13, plane polarized light); (c) Coarse crystalline, rombohedral dolomite in crystalline dolomitic limestone (sample DHL 12B, crossed polarized light); (d) Channel porosity within crystalline calcite (sample DHL 12B, crossed polarized light).

Εικ. 3. Φωτομικρογραφίες των ασβεστολίθων που μελετήθηκαν: (α) Ενδοκλάστες και ωολίθοι σε rudstone (δείγμα DHL 13, παράλληλα nicols), (β) Πλήθος απολιθωμάτων μέσα σε rudstone συγκολλημένων με σπαρτιτικο ασβεστίτη (δείγμα DHL 13, παράλληλα nicols), (γ) Ρομβοεδρικοί κρύσταλλοι δολομίτη (δείγμα DHL 12B, διασταυρωμένα nicols), (δ) Πορώδες τύπου καναλιού μέσα σε κρυστάλλους ασβεστίτη (δείγμα DHL 12B, διασταυρωμένα nicols).
X-Ray Diffraction

X-Ray diffraction patterns of random powder mounts revealed the presence of calcite in all samples except for dolomitic limestones where dolomite is also present. The insoluble residue is dominated by smectite, chlorite, illite and vermiculite. In some samples traces of mixed-layer illite-chlorite were also present. The presence of smectite was detected by a diffraction maximum at 15 Å in the air dried sample, which is shifted at 16.9 Å after treatment with ethylene glycol and at 10 Å after heating at 490oC. Illite is identified by the reflections at 10 Å, 5 Å and 3.3 Å, which remain unaffected after ethylene glycol treatment and heating (Moore and Reynolds, 1989). Chlorite was identified by the reflections at 14.2 Å, 7.1 Å, 4.77 Å and 3.55 Å and vermiculite by the peak at 14.5 Å, which remains unaffected after ethylene glycol treatment. The mixed layer illite–chlorite was identified by the diffraction maximum at 12 Å and at about 7 to 7.98 Å, which was not affected by ethylene glycol treatment (Thorez, 1976, Reynolds, 1980, Ruiz-Cruz, 2001).
Physical properties

Knowledge of the physicochemical properties of carbonate rocks is essential in order to determine their quality. Physical properties were determined in ten representative samples and the results are given in Table 1. Moisture content of the studied limestone ranges between 0.07-0.42% whereas their water absorption (Wa) values range between 0.07-2.67% (Tab. 1). Total porosity (nt) is an important factor in rock strength, since a small change in pore volume can produce an appreciable mechanical effect (ISRM, 1981). The nt values obtained for the limestones range between 0.37 - 0.85%. Total Organic Carbon (TOC) ranges between 0.09-0.29% and insoluble residue range between 1.08-5.69%. Rudstone and grainstone have the lowest content in TOC and insoluble residue. The positive values of colour parameter b* (yellowness) in the packstones, which have low TOC contents and insoluble residue, show that these samples are in the range of light yellow colour (Tab. 1). Mudstone and wackestone have higher parameter b* values than other lithotypes. With increasing total organic carbon and insoluble residue redness-greenness and yellowness of the samples increase. The TOC and insoluble residue are inversely correlated to the colour index L with the following empirical equations: TOC = -0.0142 L + 1.421 and IR = -0.2691 L + 27.266 (Fig. 5).

<table>
<thead>
<tr>
<th>Sample</th>
<th>DHL 4B</th>
<th>DHL 125</th>
<th>DHL 13</th>
<th>DHL 20B</th>
<th>DHL 21</th>
<th>DHL 230</th>
<th>G1S</th>
<th>P11B</th>
<th>P22A</th>
</tr>
</thead>
<tbody>
<tr>
<td>moisture content (%)</td>
<td>0.10</td>
<td>0.14</td>
<td>0.08</td>
<td>0.62</td>
<td>0.14</td>
<td>0.83</td>
<td>0.53</td>
<td>0.40</td>
<td>0.11</td>
</tr>
<tr>
<td>water absorption (%)</td>
<td>0.46</td>
<td>7.62</td>
<td>6.28</td>
<td>0.63</td>
<td>0.52</td>
<td>0.69</td>
<td>1.37</td>
<td>1.37</td>
<td>0.67</td>
</tr>
<tr>
<td>total porosity</td>
<td>1.51</td>
<td>2.05</td>
<td>1.38</td>
<td>0.76</td>
<td>2.15</td>
<td>7.59</td>
<td>2.63</td>
<td>5.29</td>
<td>3.55</td>
</tr>
<tr>
<td>ep. spec. gravity (g/cm³)</td>
<td>2.65</td>
<td>2.62</td>
<td>2.03</td>
<td>2.62</td>
<td>2.94</td>
<td>2.04</td>
<td>2.64</td>
<td>2.01</td>
<td>2.65</td>
</tr>
<tr>
<td>bulk spec. gravity (g/cm³)</td>
<td>2.79</td>
<td>2.69</td>
<td>2.72</td>
<td>2.64</td>
<td>2.98</td>
<td>2.88</td>
<td>2.99</td>
<td>2.26</td>
<td>2.34</td>
</tr>
<tr>
<td>total porosity (%)</td>
<td>93.61</td>
<td>95.32</td>
<td>93.72</td>
<td>80.88</td>
<td>79.57</td>
<td>68.30</td>
<td>95.64</td>
<td>96.97</td>
<td>96.79</td>
</tr>
<tr>
<td>a</td>
<td>0.62</td>
<td>9.33</td>
<td>6.27</td>
<td>0.56</td>
<td>2.91</td>
<td>2.07</td>
<td>0.17</td>
<td>6.83</td>
<td>0.73</td>
</tr>
<tr>
<td>b</td>
<td>4.88</td>
<td>6.60</td>
<td>5.85</td>
<td>2.65</td>
<td>11.32</td>
<td>5.69</td>
<td>5.93</td>
<td>4.81</td>
<td>7.65</td>
</tr>
<tr>
<td>W0</td>
<td>62.99</td>
<td>75.33</td>
<td>75.40</td>
<td>25.93</td>
<td>11.65</td>
<td>41.21</td>
<td>48.07</td>
<td>66.47</td>
<td>41.39</td>
</tr>
<tr>
<td>insol. residue (%)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.33</td>
<td>0.28</td>
<td>0.29</td>
<td>0.26</td>
<td>0.13</td>
<td>6.14</td>
<td>0.14</td>
</tr>
<tr>
<td>TOC (%)</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.57</td>
<td>0.39</td>
<td>0.40</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>insol. residue (%)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.33</td>
<td>0.28</td>
<td>0.29</td>
<td>0.26</td>
<td>0.13</td>
<td>6.14</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Table 1. Mean values of physical properties of the investigated carbonate samples from the Ileia Prefecture.

Fig. 5. Correlation diagrams of the total organic carbon and insoluble residue with the colour L* parameter.

Εικ. 5. Διαγράμματα συσχέτισμον ολικού οργανικού άνθρακα και αδιάλυτου υπολείμματος με τη χρωματική παράμετρο L.
Water absorption shows well defined inverse correlation with the CaO content, except for the mudstone samples (Fig. 6a). Moisture content is positively correlated with insoluble residue, suggesting that clay minerals are the prevalent water adsorbents (Fig. 6b). However, in samples containing abundant quartz in the insoluble residue (DHL 19, DHL 20B) the relationship is not well determined. They are related each other with the empirical equations: \[ \text{Wa} = -0.4371 \times \text{CaO} + 1.421 \] and \[ \text{IR} = 8.6576 \times \text{m.c} + 0.8631 \]

**Geochemistry**

Whole-rock geochemical analyses from representative carbonate rocks are listed in Tab. 2. The analyzed limestone samples have CaO content between 48.64 and 55.67 wt.% with minor to moderate SiO\(_2\) and Al\(_2\)O\(_3\) abundances (Fig. 7). According to the chemical classification based on CaCO\(_3\) content (Oates 1998), grainstone and rudstone are characterized as ultra-high pure calcium limestones (CaCO\(_3\) > 98.5%), except for the crystalline dolomitic limestone, which due to the presence of MgO shows much lower CaCO\(_3\) contents. Packstones are characterized as calcium limestones of high purity (CaCO\(_3\) = 97-98.5%) and median purity limestones (CaCO\(_3\) = 93.5-97.0%). Mudstones and wackestones are characterized as low calcium limestones (CaCO\(_3\) = 85.0-93.5%) except for DHL 4B which is classified as highly pure limestone.

---

**Fig. 6.** Plot of water absorption vs. CaO content and moisture content vs. insoluble residue for the Cretaceous carbonate samples from Ileia Prefecture.

**Εικ. 6.** Διάγραμμα υδατοαπορροφητικότητας ως προς CaO και περιεχόμενης υγρασίας ως προς αδιάλυτο υπόλειμμα για τα ανθρακικά πετρώματα ηλικίας Κρητιδικού του Ν. Ηλείας.
The total amount of impurities (sum of all oxides excluding CaO and CO₂) for grainstone and rudstones ranges between 0.01 and 3.34 wt.%. The SiO₂ content is 0.34-1.65% and the Al₂O₃ content ranges between 0.08 and 0.35%. The SiO₂ content is higher in the packstones than in the grainstones. Mudstones and wackestones show the highest amount of SiO₂ and Al₂O₃. High SiO₂ and Al₂O₃ contents are related with the presence of quartz and clay minerals in the insoluble residue in these samples. All samples are poor in MgO (<1%), except for the dolomitic limestone with MgO content of 3.84 wt.%, due to the presence of dolomite. The mudstones have higher amounts of Fe₂O₃ than the rest samples. The concentrations of MnO, Na₂O, are very low in all the analyzed samples. The low concentration of phosphorus reflects the absence of apatite in the samples, a mineral that is easily altered during diagenesis (Parekh et al., 1977; Cullers, 2002). Sr was detected in all samples, however the amount of Sr in the dolomitic limestone (DHL 12B) is lower than the rest samples. Sr is easily mobilized during weathering, especially in oxidizing, acid environments, thus it is incorporated in clay minerals. Sr plays an important role to the cycling (Zhao et al., 2009, Kabata-Pendias 2011). The mudstone samples display high Ba contents. The enrichment of Ba in limestones indicates high productivity in the upper part of the sea column similar to the high concentrations of barite reported at the bottom of the Mediterranean (Passier et al., 1999; Tenger et al., 2005). Ba is also strongly adsorbed by clay minerals and it commonly substitutes for K in feldspars (Kabata-Pendias, 2011). Sample DHL 20B demonstrates the highest Cu values compared to the remaining samples.
Discussion-Conclusions

The Cretaceous succession of the Olo
nos–Pindos Zone has recorded the
sedimentary history of a complex mar-
ginal basin aligned to the north east-
er Apulian passive margin, in which
tectonism, sediment supply and pal-
aeoceanographic effects have influ-
enced the slope and basin plain sedi-
mentation. The autochthonous rocks
compose pelagic limestone while the
allochthonous ones comprise thin in-
tercalation siliceous, pelitic and organic
rich facies of Early and Mid Cretaceous
age (Neumann and Zacher, 2004). The
carbonate samples include a variety of
lithotypes such as mudstones, wacke-
stones, packstones, grainstone and rud-
stones. In thin sections veinlets of calcite
are observed and stylolites are often as-
associated with insoluble material (mainly
clay minerals) accumulated as a result
of pressure-induced dissolution.

Physical properties of the studied sam-
plies were determined on both the whole-
rock and powdered material. There is an
excellent negative relationship between
water absorption and CaO content, ex-
cept for the mudstones, which are rich
in SiO₂ indicating that impurities play a
significant role in the absorption of wa-
ter. Furthermore, moisture content is
positively correlated with insoluble resi-
due probably due to the presence of ab-
sorbent clay minerals. The colour index
is negatively correlated with the insolu-
ble residue and TOC, suggesting that
they both have a negative affect on the
aesthetic appearance of limestones. Impur-
ities in carbonate rocks may show
variable compositions and amounts
and may affect their properties. A con-
siderable amount of some impurities
may be tolerated in carbonate rocks for
some uses, if they are finely disseminat-
ed throughout the rocks. On the other
hand, if the impurities are concentrated
in distinct laminae, they may form planes
of weakness that seriously affect the per-
formance of the rocks (Boynton, 1980;
Harben, 1992; Carr et al., 1994; Oates,
1998; Christidis et al., 2004).

Generally, high contents of magnesium
carbonate are undesirable in cement in-
dustries. The level of MgO in the clinker
should not exceed 5% and indeed, many
cement producers favour an upper limit
of 3%, so dolomitic and magnesian lime-
stones are unsuitable for cement pro-
duction. The CaCO₃ content in all ana-
lyzed samples lies above 87% (Tab. 2,
Fig. 8a) and the samples have low MgO
contents, thus comprising suitable ma-
terials for cement production, except the
dolomite horizons occurring in the Cre-
taceous carbonate rocks (Fig. 8b). Ac-
cording to Rigas et al. (1990) pure lime-
stones have insoluble residues less than
0.03%, while impure limestones show in-
soluble residues higher than 5.5%. The
Cretaceous limestone from Ileia show a
broad range of insoluble residues (Fig.
8c) and they are characterized as pure,
medium pure (with insoluble residue be-
tween 0.03 and 5.50%) and impure.
The CaCO₃ content in the Ileia Creta-
ceous carbonates exceeds the limit of
65% for suitability in cement production.
However, the Mg abundance, the insolu-
ble residue, the total organic carbon
and the colour index suggest that only
grainstones (G1B) and rudstone (DHL
13) are suitable for cement production
(Fig. 8). All the studied limestones are
suitable as pH regulators in acid soils,
as well as additives of fertilizers because
the CaCO₃ content exceeds 60% and
the MgO content is below 5% (Fig. 8).
The grainstones (G1B), rudstones (DHL
13) and packstones (DHL 21, PK2A) are
suitable for desulphurization of exhaust
gases because the CaCO₃ content ex-
ceeds 95%, and very low Al₂O₃ (< 1%), SiO₂ and MgO contents (< 2%; Figs 8 and 9).

From this study, it appears that petrographic investigation coupled by mineralogical and geochemical analysis are useful in assessing the quality of limestones, despite the fact that several physical properties cannot be directly evaluated.

**Fig. 8.** Variation of CaCO₃ content (a), MgO (b) and insoluble residue (c) of the analyzed Cretaceous limestone samples. Dashed lines indicate the suitability limits for use of carbonate rocks in cement industry. Dotted lines indicate the suitability limits for use of carbonate rocks as fertilizers (Boynton, 1980; Harben, 1992; Oates, 1998).

**Εικ. 8.** Διακύμανση της περιεκτικότητας σε CaCO₃ (α), MgO (β) και αδιάλυτου υπολείμματος (γ) των αναλυμένων ασβεστόλιθων Κρητιδικής ηλικίας. Οι διαγραμμιζόμενες ευθείες δείχνουν τα ορία που απαιτούν οι προδιαγραφές για χρήση ανθρακικών πετρωμάτων στην τσιμεντοβιομηχανία. Οι διάστικτες ευθείες δείχνουν τα ορία που απαιτούν οι προδιαγραφές για χρήση ανθρακικών πετρωμάτων ως εδαφοβελτιωτικών (Boynton, 1980; Harben, 1992; Oates, 1998).

**Fig. 9.** Variation of Al₂O₃ (a) and SiO₂ (b) contents of the analyzed Cretaceous limestone samples. Dashed lines indicate the suitability limits for use of carbonate rocks in desulphurization of exhaust gases (Boynton, 1980; Harben, 1992; Carr et al., 1994; Oates, 1998).

**Εικ. 9.** Διακύμανση του Al₂O₃ (α) και SiO₂ (β) των αναλυμένων ασβεστόλιθων Κρητιδικής ηλικίας. Οι διαγραμμιζόμενες ευθείες δείχνουν τα ορία που απαιτούν οι προδιαγραφές για χρήση ανθρακικών πετρωμάτων στην αποθέωση των καυσαερίων (Boynton, 1980; Harben, 1992; Carr et al., 1994; Oates, 1998).
Acknowledgments
The senior author wishes to thank the Greek State Scholarship Foundation (I.K.Y.), for financial support. Professor Nikolaos Skarpelis and an anonymous reviewer are gratefully acknowledged for their substantial criticism of the manuscript.

References
Aashato T147. The Field Determination Of Density Of Soil In-Place (1954-70).
Aashato T T85. Specific gravity and absorption of coarse aggregates


Piper, D.J.W., 2006. Sedimentology and tectonic setting of the Pindos Flysch of the Peloponnese, Greece, In: Robertson, A.H.F., Mountrakis, D. (Eds.), Tectonic Development of the Eastern Mediterranean Region. Geologi-


