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GENESIS AND PHYSICAL CHARACTERISTICS OF THE NEOGENE RED BEDS FROM THE CEDAR HILLS OF THESSALONIKI, MACEDONIA, GREECE

Tsirambides A.

Department of Mineralogy-Petrology-Economic Geology, School of Geology, A.U.Th., Thessaloniki 541 24, ananias@geo.auth.gr

ABSTRACT

The genesis and the physical characteristics of the Neogene red beds of the cedar hills surrounding Thessaloniki are studied in this paper. The peri-urban forest, which covers these hills, has a 3,022 ha area. The topographic relief is smooth and is divided in eight small drainage basins, tapped through small creeks. The elevation of the surrounding hills varies between 85 and 560 m. The dominant land slopes vary between 20 and 55%. All the samples are coarse grained, poorly sorted and friable and present earthy lustre and red colour because of the extensive presence of iron oxides. Angular to sub-angular rock fragments derived from the metamorphic bedrock are very common. Petrographically, the studied red beds belong to the clayey sands. The extended presence (41-66%) of coarse silt and sand size grains (>20 μm) in the samples suggests a mild intensity of in situ weathering of the bedrock. X-ray diffraction analysis of the coarsest fractions 250-20 μm and 20-2 μm revealed in decreasing abundance the presence of quartz, feldspars, epidote, micas, chlorite, pyroxenes, amphiboles, and talc. These fractions contain the 2M polytype of mica, while in the fraction <2 μm the $1M_d$ polytype of illite predominates. In the clay fraction (<2 μm) illite, smectite, and chlorite predominate. The presence of mixed-layer minerals is limited, testifying the almost complete character of hydrolysis of the primary minerals. The formation of red beds took place on low relief land under alternating wet and dry seasons, which prevail in the eastern Mediterranean region since Neogene. The clay minerals are the in situ weathering products of the primary minerals of the greenschists, gneisses and gabbros predominating in the studied area. The extensive presence of clay size grains (11-26%) in the samples, their poor sorting, and their sub-angular morphology, indicate that the red beds are texturally immature. In addition, the abundance of feldspars and Fe-Mg minerals reflects mineralogical immaturity. The low relief and the long-lasting tectonic stability in the Thessaloniki district were essential for the significant thickness of the red beds. The oxygen isotope data of the <0.2 μm fraction (+18.2 to +18.8‰) confirm the pedogenic origin of the clay minerals present. The red beds studied present low plasticity with liquid limit (W_l) 26.9 to 33.4% and plasticity index (I_p) 9.1 to 17.3%. In addition, they have high consolidation index (I_c) values (1.03 to 2.28). The swelling potential is low to medium and the activity varies between 0.5 and 1.0. The consolidation and induration degree of the samples analyzed is low, because of the great range of their mineralogical composition and the mild conditions of pressure and temperature to which they have been submitted. The studied red beds are not considered problematic for the foundation of various constructions on them.

1 INTRODUCTION

Red beds are sedimentary strata deposited on land under a strongly oxidizing environment. They may be composed of breccias, sandstones, silts and clays and are predominantly red in colour due to the presence of ferric oxide (mainly tiny hematite crystals), which coat individual grains. The main source of iron in the pigment is the in-place alteration of iron-rich primary minerals such as amphiboles, pyroxenes, chlorites, epidote, micas, etc. (Walker 1976).

In middle latitude regions mild temperatures, rainfall ranging from 50 to 100 cm/year, and chemical weathering predominate (Chamley 1989). The resulting soils typically exhibit a brown colour that tends to become reddish in the warmer areas (i.e. red Mediterranean soils). In the sub humid region of the Mediterranea, degradation is moderate. In lowland areas, where the rainfall is between 30 and 50 cm/year, the ions removed from primary silicates during humid seasons are reconcentrated during dry seasons giving genesis to smectitic minerals (Paquet & Millot 1972).

Unweathered minerals in soil profiles developed on igneous rocks undergo no appreciable oxygen isotope exchange with meteoric water in the weathering environment (Lawrence & Taylor 1972). Thus, $^{18}O/^{16}O$ ratios may be used to distinguish diagenetic or pedogenic from detrital mineral phases because the latter originating from igneous and metamorphic rocks often present lower such ratios than most minerals formed at low temperatures (Hoefs 1980).

Swelling of clayey soils upon exposure to moisture causes extensive damage to various constructions when they are built on such materials. The extent of swelling depends mainly on geological characteristics and engineering properties (i.e., clay content and mineralogy, water content, Atterberg limits, specific gravity, etc.). Recent studies have shown that the swelling potential of clayey sediments is greatly affected by their geological characteristics (Sarman 1991, Xeidakis 1996, Hossain et al. 1997, Shakoor & Sarman 1997). The theoretical model of Shuai and Fredlund (1998) may greatly assist in the prediction of in situ total heave or collapse, the in situ swelling pressure and the rate of swell or collapse of the soils. However, given the variability of geological materials and the swell potential techniques data, the prediction of ground heave is extremely difficult.

This study considers the mineralogical composition and the physical characteristics of the red beds of the cedar hills of Thessaloniki. Using a variety of petrographic, mineralogical, oxygen isotope, and geotechnical techniques it is attempted to elucidate the processes through which these red beds were formed and to evaluate the precautions which must be considered prior to construction on such clayey materials, which may stress and swell or shrink extensively.

2 GEOLOGICAL AND TOPOGRAPHIC SETTING

The peripheral hilly area of Thessaloniki belongs to the Chortiatis unit of the Circum - Rhodope geotectonic zone. The lower parts of this unit consist of Permo - Triassic metamorphic rocks (i.e. gneisses, greenschists, phyllites, sericite- chlorite- actinolite- schists, marbles, and quartzites). The upper parts consist of Triassic - Jurassic sediments (i.e. cherts and limestones). In addition, ophiolitic bodies with basic and ultrabasic rocks (i.e. gabbros, diorites, pyroxenites, and peridotites) are very common. Neogene red beds, ranging in thickness from a few centimetres to 15 meters, cover parts of the above formations (Fig. 1) (Sapountzis 1969, I.G.M.R. 1978a, 1978b).

Sapountzis (1969) studied the greenschists of Thessaloniki and distinguished six petrographic types on the basis of abundance of diagnostic minerals such as quartz, albite, chlorite, and epidote, as well as sericite and amphiboles.

The peri-urban forest of Thessaloniki, which covers the north eastern hills, has a 3,022 ha area. The topographic relief is smooth and is divided in eight small drainage basins, tapped through small creeks. They flow into Thermaikos Gulf through large cement pipes. The elevation of the surrounding hills varies between 85 and 560 m. The dominant land slopes vary between 20 and 55% (Grammatikopoulos & Tourlakidis 1997).

3 MATERIALS AND METHODS

The red beds studied extend over an area of about 5 km^2 (Fig. 1). Eight samples were collected from well-exposed red bed outcrops with thickness up to 15 m and were analyzed in detail using petrographic and X-ray diffraction (XRD) techniques. Prior to mineralogical analysis samples were dried overnight in an oven at about 65^oC and then were disaggregated by use of an agate mortar and pestle. Disaggregation was done gently in order to retain, to the extent possible, the intrinsic grain sizes of the samples. A 20 g split of the <2 mm fraction of each sample was subjected to the following chemical treatments (Jackson 1979) to remove the non-silicate phases: 1N sodium acetate-acetic acid buffer solution (pH = 5.0) for carbonate removal; 30% H_2O_2 for organic matter and Mn-oxides removal; and 0.3M sodium citrate-1M $NaHCO_3$ buffer solution (pH = 7.3), to which 4 g of $Na_2S_2O_4$ were added during digestion in a water-bath at 75-80^oC, to remove free Fe-oxides and interlayer Fe- and Al-hydroxides. The above treatments are known not to affect $\delta^{18}O$ values of clays (Girard & Fouillac 1995).

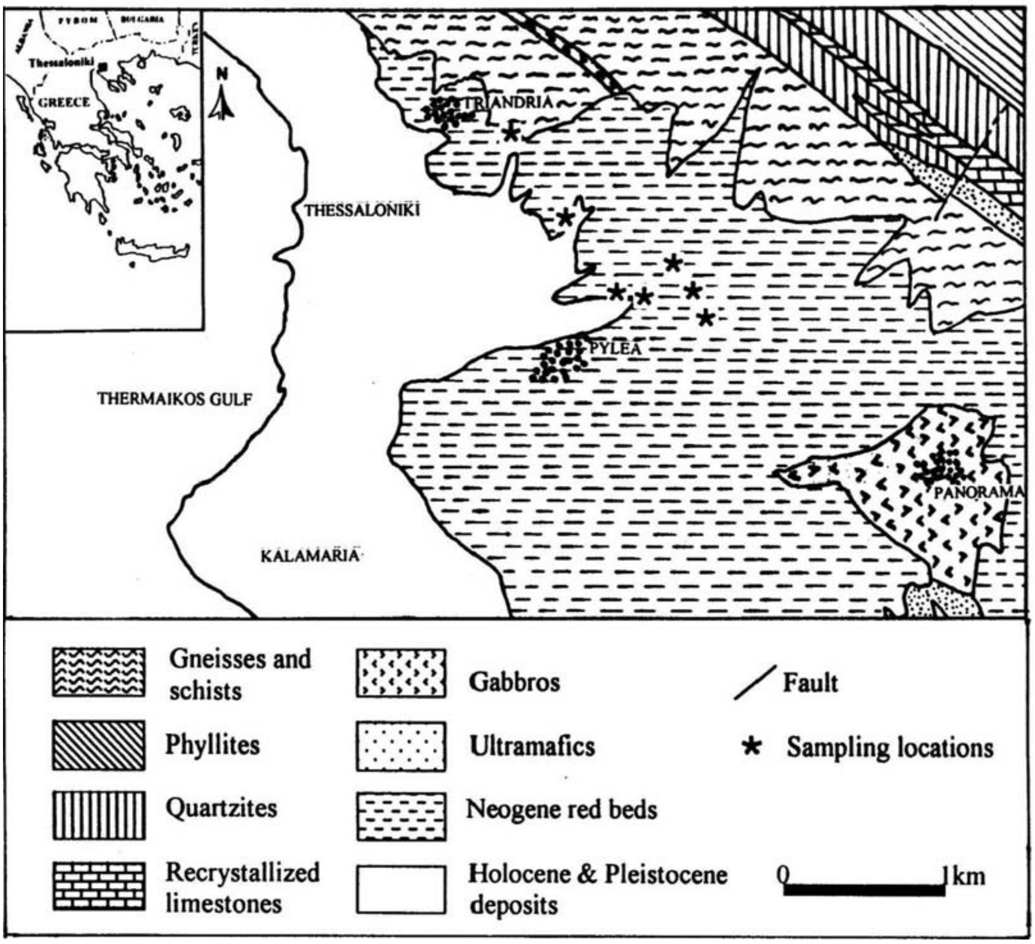

Fig. 1. Lithologic sketch map of the cedar hills of Thessaloniki.

The cleaned residues were separated into four consecutive size fractions (>250, 250-20, 20-2 and <2 μm) by sieving, gravity settling, and centrifugation, were dried overnight in an oven at about 65°C and were weighed. X-ray diffraction was performed on a Philips diffractometer with Ni-filtered CuK_{α} radiation. Both randomly oriented samples and samples with preferred orientation were scanned over the interval 3 to 43° 2θ at a scanning speed 1° per minute. Some samples were re-analyzed after glycolation and after heating at 550°C for 2.5 hours. Semi-quantitative estimates of the amounts of quartz, plagioclase, orthoclase and total clays, as well as of the amphibole, pyroxene, epidote and talc, are based on peak heights and intensity factors on XRD patterns of randomly oriented powder samples, using the methods of Schultz (1964) and Cook et al. (1975), respectively. XRD patterns taken from preferentially oriented and glycolated samples were used for the semi-quantitative estimation of clay mineral phases using specific reflections and intensity factors (Moore & Reynolds 1997).

Oxygen isotope analyses were made on 10-15 mg splits of some size fractions. The structural oxygen was liberated by reaction with BrF_5 at about 575° C and converted to CO_2 for mass spectrometric analysis (Clayton & Mayeda 1963). Oxygen isotope ratios were measured using a double collecting mass spectrometer. Analytical uncertainty on $\delta^{18}O$ determinations is estimated to be ±0.2‰. Results are reported in δ-notation as per mil deviations from the SMOW standard. The measured δ-values were related to SMOW through repeated analyses of the National Bureau of

Standards (NBS) No 28 quartz standard for which the internationally admitted value is +9.64‰ SMOW according to Coplen et al. (1983).

Atterberg limits (liquid limit, W_l and plasticity limit, W_p) were determined for a total of seven red bed samples. Measurements were performed on untreated bulk samples according to the ASTM D 4318 (1993) standard test method at the laboratory of Public Works, District of Central Macedonia. These parameters allow the calculation of the plasticity index (I_p) and the consolidation index (I_c), which are useful indicators of the mechanical/ rheological properties of the rocks.

4 RESULTS

4.1 Petrography

All the samples are coarse grained, poorly sorted and friable and present earthy lustre and red colour because of the extensive presence of iron oxides (mainly hematite). Red pigment most often forms in situ from alteration of Fe-Mg minerals (Walker 1976). Angular to sub-angular rock fragments derived from the metamorphic bedrock are very common. According to the Unified Soil Classification System (ASTM D 2487, 1985) the studied red beds belong to the clayey sands (group symbol SC). For all samples the amount of grains passing the No 200 (75 μm) sieve is <50% and their liquid limit (W_l) is <50% (Tab. 1).

Table 1. Physical characteristics of the samples analyzed.

Sample[1]	Sand %	Silt %	Clay %	Class[2]	W_l %	W_p %	I_p %	W %	I_c
$R1_1$	55	28	17	SC	28.1	17.0	11.1	5.0	2.08
$R2_{1.5}$	56	26	18	SC	28.3	17.5	10.8	7.8	1.90
$R3_2$	61	24	15	SC	27.4	16.9	10.5	7.1	1.93
$R4_1$	52	26	22	SC	31.0	17.4	13.6	9.6	1.57
$R5_3$	63	21	16	SC	26.9	17.8	9.1	6.1	2.28
$R6_1$	54	26	20	SC	31.6	16.0	15.6	13.5	1.16
$R7_{3.5}$	60	15	25	SC	33.4	16.1	17.3	15.5	1.03

[1] R1 to R7 are collecting sites; indexes denote depth below the surface (in meters).
[2] SC = clay sand.
W_l = liquid limit; W_p = plasticity limit; I_p = plasticity index (W_l-W_p); W = water content; I_c = consolidation index [(W_l-W)/I_p].

Grain size distribution of the samples is given in table 2. The average amount of the sum carbonates + organic matter + iron oxides and iron- and aluminum hydroxides is low (5-13%), indicating an environment of high oxidation potential (Eh) during the weathering processes (Degens 1967). The extended presence (41-66%) of coarse silt and sand size grains (>20 μm) in the samples suggests a mild intensity of in situ weathering of the bedrock.

Table 2. Grain size distribution (wt. %) of the samples analyzed.

Sample	COI[1]	>250 μm	250-20 μm	20-2 μm	<2 μm
$R1_1$	8	19	32	19	22
$R2_{1.5}$	13	14	36	17	20
$R3_2$	8	26	37	14	15
$R4_1$	12	30	26	14	18
$R5_3$	5	45	21	18	11
$R6_1$	10	16	28	20	26
$R6_9$	13	9	34	24	20
$R7_{3.5}$	10	5	36	23	26

[1] Total percentage (by difference) of carbonates + organics + Fe oxides and Fe- and Al- hydroxides. Other symbols as in Table 1.

4.2 X-ray mineralogy

The results of XRD analysis of sample size fractions are given in tables 3 and 4 and representative XRD patterns are shown in figure 2. The dominant minerals present in decreasing abundance in the two coarsest fractions 250-20 and 20-2 μm are quartz, feldspars (plagioclase + orthoclase), epidote, micas, chlorite (+vermiculite + kaolinite), pyroxenes, amphiboles, and talc. In the clay fraction, illite, smectite (+illite/smectite), and chlorite (+vermiculite+kaolinite) predominate. The two coarsest fractions contain the 2M polytype of mica, while in the fraction <2 μm the $1M_d$ polytype of illite predominates according to diagnostic reflections for mica polytypes of Moore & Reynolds (1997).

Table 3. Mineralogical composition (wt. %) of the size sub-fractions (in μm) analyzed.

Sample	Size	Q	Pl	Or	Am	Px	Ep	T	T.cl	I	S	Ch
$R1_1$	250-20	64	17			2	4		13			
	20-2	36	10	8		4	3	4	35			
	<2									62	15	23
$R2_{1.5}$	250-20	52	23		5		4		16			
	20-2	30	17	10	9	4	4		26			
	<2									56	16	28
$R3_2$	250-20	54	12	5	5		3		21			
	20-2	29	12	11		4	6		38			
	<2									56	20	24
$R4_1$	250-20	47	32		3		3	tr	15			
	20-2	29	13	8	7	4	4	4	31			
	<2									62	16	22
$R5_3$	20-2	30	16	10		4	4		36			
	<2									61	24	15
$R6_1$	20-2	35	12	11		3	3	4	32			
	<2									73		27
$R6_9$	20-2	26	14	9		4	3	4	40			
	<2									65	15	20
$R7_{3.5}$	20-2	24	20	9			5		42			
	<2									31	27	42

Q = quartz, Pl = plagioclase, Or = orthoclase, Am = amphibole, Px = pyroxene, Ep = epidote, T = talc, T.cl = total clays, I = illite, S = smectite (+I/S), Ch = chlorite (+vermiculite+ kaolinite). Other symbols as in Table 1.

Upon heating the glycolated samples at 550°C for 2.5 hours, the first order reflection, which coincides with chlorite, vermiculite and smectite, increased in intensity and shifted to 13.9 Å indicating the presence of chlorite (Fig. 2).

Table 4. Mineralogical (wt. %) and oxygen isotope (‰) composition of clay fractions (in μm) analyzed.

Sample	Size	I	S	Ch	$\delta^{18}O$
$R1_1$	5-1				+10.0
	1-0.2				+12.2
	<0.2	43	18	39	+18.8
$R2_{1.5}$	5-1				+9.6
	1-0.2				+10.7
	<0.2	37	35	28	+18.2
$R3_2$	5-1				+9.5
	1-0.2	79	6	15	+11.5
	<0.2	39	38	23	+18.2
$R4_1$	5-1				+9.3
	1-0.2	78	7	15	+11.1
	<0.2	48	30	22	+18.2

Symbols as in Tables 1 and 3.

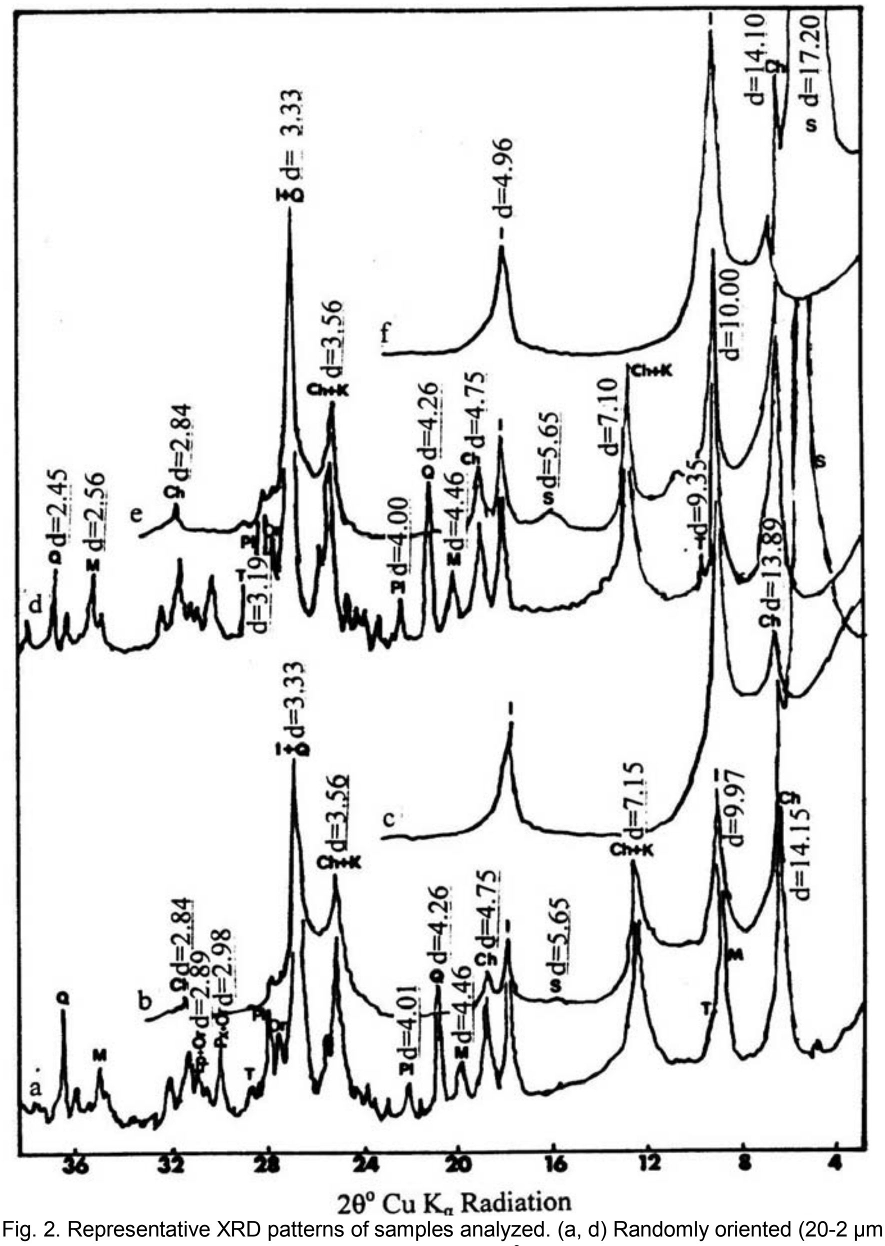

Fig. 2. Representative XRD patterns of samples analyzed. (a, d) Randomly oriented (20-2 μm); (b, e) ethylene-glycolated (<2 μm); (c, f) heated at 550°C (<2 μm). M = mica. Other symbols as in Table 3.

4.3 Isotopic analysis

The isotopic composition of separates of some sample size fractions is shown in table 4. The most significant trend is the increase in $\delta^{18}O$ values as the grain size decreases. The <0.2 μm fraction, which consists entirely of illite, smectite, and chlorite, presents the highest $\delta^{18}O$ values (+18.2 to +18.8‰). These values are within the range of $\delta^{18}O$ values commonly exhibited by clay minerals of pedogenic origin. Tsirambides & Michailidis (1999) studied the vermiculitized micas in the ultramafic rocks in the adjacent area of Askos, which belongs to the same geotectonic zone, and they found $\delta^{18}O$ values ranging from +5.0 to +17.9‰, with the higher values corresponding to the <2 μm clayey fraction as in this study.

4.4 Swelling characteristics

The red bed samples present low plasticity with liquid limit (W_l) 26.9 to 33.4% and plasticity index (I_p) 9.1 to 17.3% (Tab. 1). In addition, they have high consolidation index (I_c) values, which range from 1.03 to 2.28.

The plasticity index (I_p) of the red bed samples is plotted against clay fraction on the expansive clay classification chart (Van der Merwe 1975) in figure 3. It indicates that the swelling potential of the Thessaloniki red beds is low to medium (reflecting their rather low content in smectites), while their activity varies between 0.5 and 1.0.

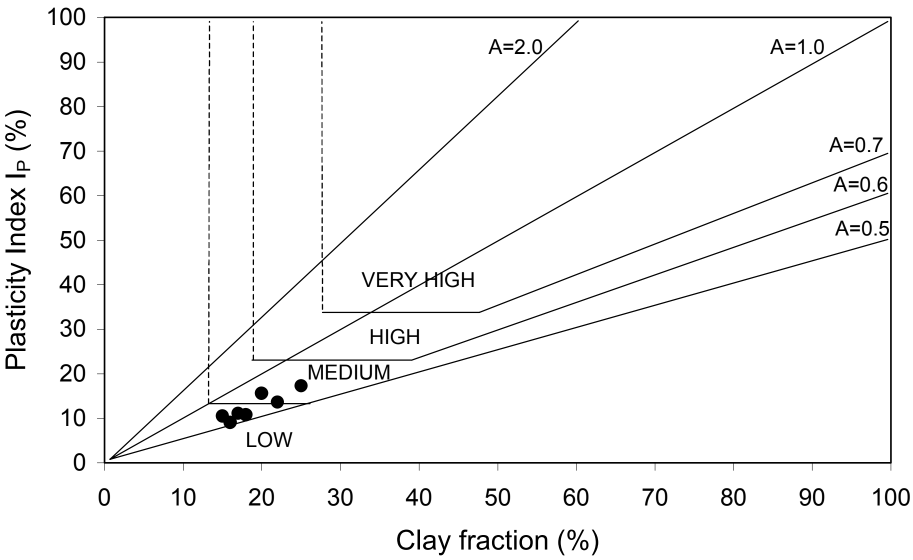

Fig. 3. Swelling potential evaluation of the studied red beds on expansive clay classification chart (after Van der Merwe 1975). A = activity.

5 DISCUSSION

5.1 Genesis

The formation of red beds may take place on low relief land under alternating wet and dry seasons. Such conditions prevail in the eastern Mediterranean region since Neogene (Nairn 1961). Even nowadays, in this area the climate is semi-arid with dry summers and mild winters.

In the poorly drained lowland of the studied area mean annual air temperature is 15.6^{o} C, mean annual humidity 67%, and mean annual rainfall 45 cm (Grammatikopoulos & Tourlakidis 1997). The most likely source materials for the formation of the studied red beds are feldspars, micas, and various Fe-Mg silicates, which are primary constituents of the metamorphic and ultramafic rocks predominating in the studied area. Dissolved ions liberated during the wet seasons are re-concentrated in the dry seasons participating in the formation of clay minerals. Most of the illite, smectite, and chlorite present were formed in situ by the weathering of the above primary minerals of the bedrock, especially greenschists, gneisses and gabbros. The presence of mixed-layer minerals in the red beds is limited, testifying the almost complete character of hydrolysis of the primary minerals.

The extensive presence of clay size grains (11-26%) in the samples, their poor sorting and their sub-angular morphology indicate that the red beds studied are texturally immature. The abundance of feldspars and Fe-Mg minerals also reflects mineralogical immaturity.

The low relief and the long-lasting tectonic stability in the Thessaloniki district were essential for the significant thickness of the red beds. In addition, the extended presence of clay minerals in the red beds confirms low intensity leaching.

The oxygen in the clay minerals of pedogenic origin, particularly in soils from mid and high latitudes, is generally richer in ^{18}O than in igneous rocks (Lawrence & Taylor 1972, Savin & Hsieh 1998). Clays and related minerals formed as weathering products approach isotopic equilibrium with the environment in which they are formed. On the other hand, as Savin (1980) pointed out, chemically and mineralogically unaltered parent materials remain isotopically unaltered in the weathering environment.

The oxygen isotope composition of the samples studied (+9.3 to +18.8‰) indicates that the weathering products from the parent material retained the isotopic composition they had in the parent rock. Also, Lawrence & Taylor (1972) found that weathering had very little effect on the hydrogen and oxygen isotopic composition of the shales until it proceeded to great extent (i.e. obvious clay minerals alteration).

5.2 Physical characteristics and implications

The swelling characteristics of expansive clays depend on numerous factors making the prediction of volume change and swelling pressure difficult. With higher content in grey-green clay (especially smectite), higher liquid limit (W_l) and plasticity index (I_p) values are taken. According to Hossain et al. (1997) grey-green clays with liquid limit <120% and particularly at low moisture content, present higher values of swelling percentage and pressure.

The consolidation and induration degree of the samples analyzed is low, because of the great range of their mineralogical composition and the mild conditions of pressure and temperature to which they have been submitted. The consolidation index (I_c) is lower in the samples with higher water content.

Finally, the red beds studied present low to medium swelling potential and activity between 0.5 and 1.0 (Fig. 3).

These materials should not be expected to cause major problems for the foundation of various constructions on them, such as the case of the National Ring Road of Thessaloniki.

6 CONCLUSIONS

The Neogene red beds of Thessaloniki formed on low relief land and under alternating wet and dry seasons. Their clay mineral constituents are in situ weathering products of the primary minerals of the greenschists, gneisses and gabbros predominating in the studied area. The red beds are texturally and mineralogically immature. The low relief and the long-lasting tectonic stability in the Thessaloniki district were essential for the significant thickness of the red beds. Oxygen isotope data confirm the pedogenic origin of the clay minerals present. The red beds studied present low to medium swelling potential and should not be problematic for the foundation of various constructions on them, such as in this case the National Ring Road of Thessaloniki.

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