

# High and low temperature minerals from the pyrometamorphic zones (natural analogues/ cement zones) of Central Jordan, Maqarin and Suweileh areas

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## Summary

The pyrometamorphic rocks and the associated kerogen-rich biomicrites and travertines are widely distributed in the three areas. The varicolors of the studied areas (black, white, and all shades of yellow, gray, brown, red and green) can be related to the presence of high and low temperature. Tables 1 summarize the minerals identified in the Maqarin, Daba-Siwaqa and Suweileh areas to date. Trace elements incorporated in the structure of these minerals are partially responsible for the different colors.

The hydrated low temperature minerals contain high concentrations of trace elements which are responsible for a variety of colors. Solid solution series are very common in the hydrated retrograde products (ettringite-thaumasite, different apatite structures with varying fluorine content, high potassium fluorine apophyllite;  $\text{CrO}_4^{2-}$  replaces  $\text{SO}_4^{2-}$ , and isomorphous substitution of  $\text{CO}_3^{2-}$ ,  $\text{SiO}_4^{4-}$  and  $\text{CrO}_4^{2-}$ .... etc ...). Apatite (ellestadite and fluoroapatite) is the major cause for coloration of marble (excluding the coloration of secondary minerals filling voids, veins and fractures). The metamorphic rocks are the product of metamorphism of the chalk-biomicrite and its stratigraphic equivalents in north and central Jordan. The identified high and low temperature minerals Central Jordan, Maqarin and Suweileh areas are summarized in Table 1.

The high temperature minerals were formed as a result of decarbonation-dehydration-recrystallization processes at high temperature, low pressure conditions. The minerals include among others: diopside, wollastonite, monticellite, gehlenite-akermanite, spurrite, and merwinite, such minerals are members of the decarbonation univariant progressive reaction series and are characteristic of contact metamorphic rocks. Other important minerals are garnet, anorthite, pervoskite, magnesioferrite, fluorapatite and recrystallized calcite. The assemblage indicates an isochemical decarbonation-dehydration metamorphism of impure limestones and biomicrites. The formation of the above-mentioned mineral assemblage from such sedimentary rocks is possible. Textural and structural analyses (porphyroblastic, poikiloblastic and granulated textures, broken and fractured crystals, columnar structure), in addition to the nature of crystal growth (cavity, vein and fracture fillings and concretionary growth) suggest a relatively rapid heating where maximum temperature was achieved. The maximum temperature was concentrated along weakness zones in the rocks where the maximum amount of oxygen was available. Spurrite is the most commonly observed rock-forming mineral in this assemblage and is present in many cases as concretionary growth with wollastonite. Such a paragenesis is an indication of prograde metamorphism.  $\text{CO}_2$  volatiles are important

products of prograde metamorphism in calcareous rocks during the formation of high temperature minerals.

The low temperature minerals were formed as a result of hydration-carbonation-sulphatization-replacement- alteration-weathering processes. The assemblage includes among others: calcium silicate hydrates (tobermorite, jennite, afwillite, apophyllite), sulfates (ettringite, hashemite, barite, thaumasite, gypsum), stable and metastable carbonates (calcite, vaterite, aragonite, kutnahorite), oxides and hydroxides (goethite, portlandite, hydrocalumite), and many calcium silicate hydrates. The assemblage indicates a later multi-stage retrograde reactions.

The occurrence of high and low temperature minerals is quite normal and well known from contact metamorphosed limestones. The presence of high temperature minerals assumes a contact metamorphic origin equivalent to the sanidinite and pyroxene hornfels facies. The high and low temperature minerals are also present in Portland cement clinkers and hydrated cement products.

A model other than igneous intrusion has to be looked for to explain the source of heat needed to form high temperature minerals under the same conditions as contact metamorphism. The most reasonable and accepted model to explain such a phenomenon is the combustion theory. Spontaneous combustion of organic matter, especially bituminous shale, is well known in the literature and also occurs in coal mines. Combustion depends on the availability of oxygen, the presence of organic matter and a triggering event.

The stratigraphic equivalents to the marble are rich in organic matter (up to 30% in the biomicrite), providing a significant potential for spontaneous combustion. Miocene tectonism was possibly the event that initiated the combustion in north and central Jordan (Maqarin, Suweileh and Daba-Siwaqa areas). The studied areas are crossed by several major Miocene faults. Tectonism formed fissures and fractures that acted as channels and pathways for oxygen supplies needed for combustion and for the trigger event, probably oxidation of sulphides. Secondary channels were possibly formed as a result of volume decrease following mass loss as a function of evolved volatiles and rapid cooling following combustion. Continuous heating and cooling would lead to a continuous expansion-contraction phenomenon. Secondary channels and pathways would lead to a self-generating mechanism, where spontaneous combustion of organic matter occurs. The confinement and restriction of the metamorphosed zone in the Biomicrite Formation indicates that availability of oxygen is the controlling factor that determines where metamorphism occurs. This is proved by the occurrence of un-metamorphosed lenses of biomicrite in the lower part of the marble zone in the studied areas.

The analyzed samples of the decarbonated rocks are strongly enriched in light isotopes of oxygen and carbon. The higher the temperature of combustion, as indicated from the colors of apatite the higher the enrichment in light stable isotopes. The normal phosphatic samples average  $\delta^{18}\text{O}_{\text{PDB}} = 6.8\text{‰}$ ; dark gray apatitic samples average  $\delta^{18}\text{O} = -10\text{‰}$ ; violet apatitic samples average  $\delta^{18}\text{O}_{\text{PDB}} = -12.4\text{‰}$ . Decarbonation and interaction with  $\text{CO}_2$  derived from combustion of organic matter is a possible mechanism for the depletion of the rock of heavy isotopes. The decarbonation process involves the release of  $\text{CO}_2$  enriched in  $^{18}\text{O}$  whereas the  $\text{CO}_2$  derived from the oxidation of organic matter is highly depleted in  $\text{C}_{13}$ . The higher enrichment of calcite and apatite with light carbon rather than oxygen could be attributed to interaction with groundwater during the

retrograde processes. The unmetamorphosed phosphatic rocks have an isotopic composition in the range of normal marine carbonates. The decarbonated rocks show enrichment in light isotopes; the slightly metamorphosed rocks give intermediate values. Results of stable isotopes from Recent travertine varieties showed enrichment in light isotopes and plotted within the range of decarbonated rocks. The isotope study indicates that the uptake of atmospheric  $\text{CO}_2$  (kinetic reaction) is responsible for the depletion of heavy isotopes from travertine.

An explanation is needed however, for the formation of some high temperature minerals (wollastonite) at low  $X_{\text{CO}_2}$ . The  $\text{CO}_2$  rich volatiles should escape from the reaction site to derive the reaction spontaneously. Dilution of  $\text{CO}_2$  by groundwater is very possible. The evolved volatiles could produce volume change in the initially chalky limestone and the bituminous marl (biomicrite) as a result of rapid increase in temperature. The evolution of volatiles could form rapidly and exceeds the initial load pressure due to the low permeability of the rocks. Accordingly, fractures, joints and fissures would have resulted and would have acted as channels. The movement of volatiles increased the rock conductivity. Diffusion therefore was rapid along fissures and fractures to allow equilibrium of newly formed minerals.

Table 1. High and low temperature minerals from the pyrometamorphic zones (natural analogues/ cement zones) of Central Jordan+, Maqarin\* and Suweileh areas# (*Abdul-Jaber and Khoury 1998; Alexander 1992; Britvin et al., 2015; Eckhardt and Heimbach 1963; Elie et al., 2007; Fleurance et al., 2013; Fourcade et al., 2007; Heimbach, 1965; Heimbach and Rosch 1980; Hauff et al. 1983; Khoury 1993, 2006, 2012, 2014a, b, 2015; Khoury and Nassir 1982a, b; Khoury and Salameh 1986; Khoury and Abu-Jayab 1995; Khoury and Al-Zoubi 2014; Khoury et al., 1984, 2014, 2015(a,b), 2016(a, b, c); Linklater 1998; Nassir and Khoury 1982; Pitty and Alexander 2011; Smellie 1998; Sokol et al., 2016,2017; Stasiak et al., 2016; Techer et al., 2006; Wieseman and Rosch 1969).*

**Table 1a. High temperature minerals**

Minerals	General Formulae
<b><u>NATIVE ELEMENTS</u></b>	
Graphite+*	C
Copper+	Cu
Silver+	Ag
<b><u>SULPHIDES (Se, As)</u></b>	
Oldhamite+*#	CaS to CaS <sub>0.9</sub> Se <sub>0.1</sub>
Cu-K-Na-Selenide*	Cu <sub>10.2</sub> K <sub>3</sub> Na <sub>0.2</sub> Se <sub>7.7</sub> S <sub>2.3</sub> (approx.)
Krutaite*	CuSe <sub>2</sub>
Cu-K-Na-Selenide*	Cu <sub>10.2</sub> K <sub>3</sub> Na <sub>0.2</sub> Se <sub>7.7</sub> S <sub>2.3</sub> (approx.)
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Sphalerite-Stilleite+	ZnS-ZnSe
Cadmium-rich sphalerite+	ZnCdS
Wurtzite+	(Zn <sub>0.88</sub> Cd <sub>0.08</sub> Fe <sub>0.01</sub> Cu <sub>0.01</sub> )S <sub>0.99</sub> S <sub>1.01</sub> As <sub>0.01</sub>
Sphalerite+	Zn <sub>0.88</sub> Cd <sub>0.07</sub> Fe <sub>0.01</sub> Cu <sub>0.01</sub> )S <sub>0.97</sub> S <sub>0.03</sub>
Gersdorffite +	NiAs/S
Millerite+	Zn-Ni S/Se
Unidentified+	Fe-Ni-Cu -Cr-Zn-Mo-BaS/Se
Makinenite+	Ni-Se/S
Stilleite+	Zn-Se/S
Makinenite+	NiSe
Greenockite +	CdS
Acanthite or argentite +	Ag <sub>2</sub> S
Samaniite+	Cu <sub>2</sub> Fe <sub>5</sub> Ni <sub>2</sub> S <sub>8</sub>
Cu-rich djerfisherite +	K <sub>6</sub> Na(Cu,Fe,Ni) <sub>25</sub> S <sub>26</sub> Cl
Pyrrhotite+	Fe <sub>x</sub> S <sub>1-x</sub>
Galena+*	PbS
Chalcopyrite+	CuFeS
Zincite+	(Zn Cd)O
Pyrite+	Fe-Ni-V-Cu-(Mo) S <sub>2</sub>
Pyrite+*	FeS <sub>2</sub>

<b><i>PHOSPHATES VANADATES</i></b>	
Fluorapatite+*#	$\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$
Fluorapatite [(SO4)-bearing+#	$\text{Ca}_{10}(\text{PO}_4 \text{ SO}_4)_6\text{F}_2$
Fluor-carbonate apatite+*#	$\text{Ca}_{10-x-y}(\text{Na,K})_x\text{Mg}_x(\text{PO}_4)_{6-z}(\text{CO}_3)_z\text{F}_{0.4z} \text{F}_2$
Ellestadite+*#	$\text{Ca}_{10}(\text{SiO}_4)_3(\text{SO}_4)_3\text{O}_{24}(\text{Cl,OH,F})_2$
Nagelschmidite+	$\text{Ca}_7\text{Si}_2\text{P}_2\text{O}_{16}$
Fluorellestadite+	$\text{Ca}_5(\text{SiO}_4)(\text{PO}_4)(\text{SO}_4)\text{F}$
Na-sulfato-phosphates+	Na-S-P (unidentified)
Ba-Sr phase+	$(\text{Ca, Ba, Sr})_{10-x}\square_x[(\text{SO}_4)_3(\text{PO}_4)_3](\text{F}^-, \text{O}_2^-, \text{Cl}^-)_2$ ( $1 < x < 2$ )
Wakefieldite+	Ce (Ce,Ca,U)[(VO <sub>4</sub> )
<b><i>NATURAL PHOSPHIDES</i></b>	
Negevite +	$\text{NiP}_2$
Zuktamrurite +	$\text{FeP}_2$
Murashkoite +	$\text{FeP}$
Halamishite +	$\text{Ni}_5\text{P}_4$
Transjordanite+	$\text{Ni}_2\text{P}$
<b><i>OXIDES, FERRITES, ALUMINATES AND MIXED OXIDES</i></b>	
Lime+*	$\text{CaO}$
Periclase+*	$\text{MgO}$
Periclase+	(Mg,Zn,Ni,Cu)O
Grossite	$\text{CaAl}_4\text{O}_7$
Magnesiochromite+	$\text{MgCr}_2\text{O}_4$
Perovskite+	$\text{CaTiO}_3$
Magnesioferrite+	$\text{MgFe}_2\text{O}_4$
Spinel+	(Mg,Fe)Al <sub>2</sub> O <sub>4</sub>
Chromite+	$\text{FeCr}_2\text{O}_4$
Hematite or ferric oxide+*	$\alpha\text{-Fe}_2\text{O}_3$
Magnetite (?)*	$\text{Fe}_3\text{O}_4$
Maghemite (?)*	$\gamma\text{-Fe}_2\text{O}_3$
Ca-aluminate*	Undefined
Calcium ferrite*	$\text{CaFe}_2\text{O}_3$
Brownmillerite+*#	$\text{Ca}_2(\text{Fe}_{1-x}\text{Al}_x)_2\text{O}_5$ (Ti-, Cr-, and/or Zn-bearing)
Multiple element ferrites*	(Ca,Ba,Cr,Al,Ti,Mg,Zn,Mn)Fe <sub>2</sub> O <sub>3</sub> Undefined
Hercynite+	$\text{FeAl}_2\text{O}_4$
Bunsenite	$\text{NiO}$
Srebrodolskite+	$\text{Ca}_2\text{Fe}^{3+}_2\text{O}_5$
Harmunite+	$\text{Ca}_2\text{Fe}^{3+}_2\text{O}_4$
Hibonite+	$\text{CaAl}_{12}\text{O}_{19}$
Perovskite+	$\text{CaTiO}_3$
Magnesioferrite+	$\text{MgFe}^{3+}_2\text{O}_4$
Lakargiite+	$\text{Ca}(\text{Zr,U,Ti,Fe})\text{O}_3$

Powellite+	CaMoBaO <sub>4</sub>
Shulamitite+	Ca <sub>3</sub> TiFe <sup>3+</sup> AlO <sub>8</sub>
Lime-monteponite SS+	(Ca,Cd)O SS
Tululite+	(Ca,Cd) <sub>4</sub> (Fe <sup>3+</sup> ,Al)(Al,Zn,Fe <sup>3+</sup> ,Si,P,Mn,Mg) <sub>15</sub> O <sub>36</sub>
Zincite+	(Zn,Cd)O
Cerianite+	(Ce,Th)O <sub>2</sub>
Cuprite+	Cu <sub>2</sub> O
Tenorite+	CuO
Cassiterite+	SnO <sub>2</sub>
<b><u>CARBONATES</u></b>	
Calcite+*	CaCO <sub>3</sub>
Calcite+	Ca-Zn-Cd-(Mo-Ni-V) CO <sub>3</sub>
U-Ca-oxycarbonate?*	Ca:U = 2:1
U-Ca-oxycarbonate?*	Ca:U = 2:1
<b><u>SILICATE MINERALS</u></b>	
Larnite+*#	$\beta$ -Ca <sub>2</sub> SiO <sub>4</sub>
Wollastonite+*#	CaSiO <sub>3</sub>
Parawollastonite+#	Ca <sub>3</sub> Si <sub>3</sub> O <sub>9</sub>
Anorthite+*	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub>
Albite+	Na AlSi <sub>3</sub> O <sub>8</sub>
Orthoclase+	KAlSi <sub>3</sub> O <sub>8</sub>
Rankinite (?)+*#	Ca <sub>3</sub> Si <sub>2</sub> O <sub>7</sub> (significant Zn substitution for Ca)
Diopside-hedenbergite+*#	Ca(Al,Fe)Si <sub>2</sub> O <sub>6</sub>
Monticellite+	CaMgSiO <sub>4</sub>
Grossular+	Ca <sub>3</sub> Al <sub>2</sub> [SiO <sub>4</sub> ] <sub>3</sub>
Andradite+	Ca <sub>3</sub> Fe <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>
Merwinite+#	Ca <sub>3</sub> Mg(SiO <sub>4</sub> ) <sub>2</sub>
Gehlenite- Akermanite+	Ca <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub> - Ca <sub>2</sub> Al(Si,Al) <sub>2</sub> O <sub>7</sub>
Hatrurite+	Ca <sub>3</sub> SiO <sub>5</sub>
Bredigite+	Ca <sub>7</sub> Mg(SiO <sub>4</sub> ) <sub>4</sub>
Gehlenite+	Ca <sub>2</sub> Al(Si,Al) <sub>2</sub> O <sub>7</sub>
Melilite+	Ca,Na) <sub>2</sub> (Mg,Fe,Al)[(Si,Al) <sub>2</sub> O <sub>7</sub> ]
Schorlomite+	Ca <sub>3</sub> (Ti,Fe <sup>+3</sup> ) <sub>2</sub> (Si,Fe <sup>+3</sup> )O <sub>12</sub>
Cuspidine+	Ca <sub>4</sub> (Si <sub>2</sub> O <sub>7</sub> )F <sub>2</sub>
U-Ca-silicate*	unidentified and undefined
Kumtyubeite+	Ca <sub>5</sub> (SiO <sub>4</sub> ) <sub>2</sub> F <sub>2</sub>
Pumpallyite+	Ca <sub>2</sub> MgAl <sub>2</sub> (SiO <sub>4</sub> )(Si <sub>2</sub> O <sub>7</sub> )(OH) <sub>2</sub> •(H <sub>2</sub> O)
Dorrite+	Ca <sub>2</sub> (Mg <sub>2</sub> Fe <sup>+3</sup> <sub>4</sub> )(Al <sub>4</sub> Si <sub>2</sub> O <sub>20</sub> )
<b><u>COMPLEX SILICATES AND SILICATES WITH OTHER OXYANIONS</u></b>	
Spurrite+*#	Ca <sub>5</sub> (SiO <sub>4</sub> ) <sub>2</sub> (CO <sub>3</sub> ) (Na- and P-bearing)

Parraspurrite+*#	$\text{Ca}_5(\text{SiO}_4)_2(\text{CO}_3)$
Tilleyite+#	$\text{Ca}_5(\text{Si}_2\text{O}_7)(\text{CO}_3)_2$
Ternesite+*	$\text{Ca}_5(\text{SiO}_4)_2(\text{SO}_4)$
Ba-Ca-sulphate-silicate*	Undefined
Ba-Ca-Zr-Mo-silicate*	Undefined
Ca-U silicate+	Unidentified (Unknown)
<b><i>Ca-U DOUBLE OXIDES</i> <math>n\text{CaO}\cdot m\text{UO}_3</math></b>	
Vorlanite +#	$(\text{CaU}^{6+})\text{O}_4$
Unidentified+#	$\text{Ca}_2\text{UO}_5$
Vapnikite+#	$\text{Ca}_3\text{UO}_6$
Unidentified +#	$\text{Ca}_4\text{UO}_7$
Unidentified +#	$\text{Ca}_5\text{UO}_8$
Unidentified +#	$\text{Ca}_6\text{UO}_9$
Unidentified +#	$\text{Ca}_3\text{U}_2\text{O}_9$

**Table 2b: Low temperature minerals**

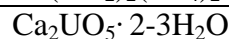
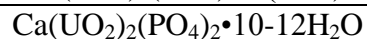
Mineralogy	General Formulae
<b><u>NATIVE ELEMENTS</u></b>	
Native Sulfur+	S
Native Selenium+	Se
<b><u>CARBONATES</u></b>	
Calcite+*#	$\text{CaCO}_3$
Aragonite+*	$\text{CaCO}_3$
Vaterite+*#	$\text{CaCO}_3$
Strontianite+*	$\text{SrCO}_3$
Ankerite*	$\text{Ca}(\text{Mg,Fe})(\text{CO}_3)_2$
Kutnahorite+*	$\text{Ca}_{0.75}(\text{Mn,Mg})_{0.25}(\text{CO}_3)_2$
Dolomite+	$\text{Ca}(\text{Mg})(\text{CO}_3)_2$
Hydrotalcite*+	$\text{MgAl}_2(\text{CO}_3)(\text{OH})_{16}\cdot 4\text{H}_2\text{O}$
<b><u>HALIDES</u></b>	
Halite+*	NaCl
Fluorite+	$\text{CaF}_2$
Lodargirite	AgI
Bromargyrite	AgBr
Embolite	Ag(Br,Cl)
<b><u>OXIDES</u></b>	
Hematite or ferric oxide+*	$\alpha\text{-Fe}_2\text{O}_3$
Maghemite (?) +*	$\gamma\text{-Fe}_2\text{O}_3$
Mayenite group minerals: Fluorkyuugenite+	$\text{Ca}_{12}\text{Al}_{14}\text{O}_{32}[(\text{H}_2\text{O})_n(\text{F,Cl})_2]$
chlormayenite+	$\text{Ca}_{12}\text{Al}_{14}\text{O}_{32}\text{Cl}_2$
Hydrated/hydroxylated fluormayenite+	$\text{Ca}_{12}\text{Al}_{14}\text{O}_{32}\text{F}_2$
<b><u>SIMPLE HYDROXIDES</u></b>	

Brucite+*	Mg(OH) <sub>2</sub>
Portlandite+*#	Ca(OH) <sub>2</sub>
Cd-rich portlandite+	(Ca,Cd)(OH) <sub>2</sub> , (Ca <sub>1-x</sub> Cd <sub>x</sub> )[OH] <sub>2</sub> SS ( $x \leq 0.5$ )
Ca[OH] <sub>2</sub> - Cd[OH] <sub>2</sub> SS+	(Ca <sub>0.67</sub> Cd <sub>0.33</sub> )[OH] <sub>2</sub> - (Ca <sub>0.45</sub> Cd <sub>0.55</sub> )[OH] <sub>2</sub>
Gibbsite+*	$\alpha$ -Al(OH) <sub>3</sub>
Goethite+*	$\alpha$ -FeO.OH
Iron oxyhydroxide*	undifferentiated
Lepidochrocite+	FeO.OH
Hydrocalumite+	Ca <sub>4</sub> Al <sub>2</sub> (OH) <sub>12</sub> Cl <sub>2</sub> •4H <sub>2</sub> O
Qatranaitite+	CaZn <sub>2</sub> (OH) <sub>2</sub> (H <sub>2</sub> O) <sub>2</sub>
Cd-basic chloride+	Cd(OH) <sub>2-x</sub> Cl <sub>x</sub>
<b><u>SULPHATES</u></b>	
Gypsum+*#	CaSO <sub>4</sub> .2H <sub>2</sub> O
Bassanite+*	CaSO <sub>4</sub> .0.52H <sub>2</sub> O
Anhydrite+*	CaSO <sub>4</sub>
Barite+*#	BaSO <sub>4</sub>
Celestite (celestine) +*#	SrSO <sub>4</sub>
Barytocelestite+*	(Ba,Sr Anhydrite)SO <sub>4</sub>
Calcian barytocelestite+	(Ba,Ca,Sr)(SO <sub>4</sub> )
Hashemite+	Ba(CrO <sub>4</sub> )
Ye'elimitite+	Ca <sub>4</sub> Al <sub>6</sub> O <sub>12</sub> (SO <sub>4</sub> )
Hashemite*	BaCrO <sub>4</sub> to BaSO <sub>4</sub> [complete solid-solution]
Cd-sulphate phase*	Undefined phase
Pb-sulphate phase*	Undefined phase
Cu,Zn-sulphate phase*	Undefined phase
<b><u>COMPLEX SULPHATES</u></b>	
Ettringite+*#	Ca <sub>6</sub> Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> (OH) <sub>12</sub> .25H <sub>2</sub> O
Thaumasite+*#	Ca <sub>6</sub> Si <sub>2</sub> (SO <sub>4</sub> )(CO <sub>3</sub> ) <sub>2</sub> (OH) <sub>12</sub> .24H <sub>2</sub> O
Jourovskite*	Ca <sub>3</sub> Mn(CO <sub>3</sub> )(SO <sub>4</sub> )(OH) <sub>6</sub> .12H <sub>2</sub> O
Bentorite+	Ca <sub>6</sub> Cr <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> (OH) <sub>12</sub> •26H <sub>2</sub> O
<b><u>SILICA MINERALS</u></b>	
Quartz+*#	SiO <sub>2</sub>
Silica gel+*	SiO <sub>2</sub> .nH <sub>2</sub> O
Opal-CT+*	SiO <sub>2</sub>
Opal-A+*	SiO <sub>2</sub> .nH <sub>2</sub> O
<b><u>APATITE MINERALS</u></b>	
Hydroxyapatite+*#	Ca <sub>10</sub> (PO <sub>4</sub> ) <sub>6</sub> (OH) <sub>2</sub>
Fluorapatite+*#	Ca <sub>10</sub> (PO <sub>4</sub> ) <sub>6</sub> F <sub>2</sub>
Fluor-carbonate Apatite+*#	Ca <sub>10-x-y</sub> (Na,K) <sub>x</sub> Mg <sub>y</sub> (PO <sub>4</sub> ) <sub>6-z</sub> (CO <sub>3</sub> ) <sub>z</sub> (OH) <sub>2</sub> F <sub>0.4z</sub> F <sub>2</sub>
Ellestadite+*#	Ca <sub>10</sub> (SiO <sub>4</sub> ) <sub>3</sub> (PO <sub>4</sub> ) <sub>3</sub> O <sub>24</sub> (Cl, F, OH) <sub>2</sub>
Fluorellestadite+*#	Ca <sub>10</sub> (SiO <sub>4</sub> ) <sub>3</sub> (PO <sub>4</sub> ) <sub>3</sub> O <sub>24</sub> (F) <sub>2</sub> [3]
<b><u>CSH and CASH PHASES</u></b>	
Afwillite+*#	Ca <sub>3</sub> Si <sub>2</sub> O <sub>4</sub> (OH) <sub>6</sub>
Tobermorite(s)+*#	Ca <sub>5</sub> Si <sub>6</sub> O <sub>16</sub> (OH) <sub>2</sub> .2-8H <sub>2</sub> O
Jennite+*#	Ca <sub>9</sub> (Si <sub>3</sub> O <sub>9</sub> ) <sub>2</sub> (OH) <sub>6</sub> •8H <sub>2</sub> O
Tacharanite+	Ca <sub>12</sub> (Al <sub>2</sub> Si <sub>18</sub> O <sub>51</sub> )•18H <sub>2</sub> O



Katoite+	$\text{Ca}_3\text{Al}_2(\text{SiO}_4)_{3-x}(\text{OH})_{4x}$ ( $x=0.2-1.5$ )
Hibschite+	$\text{Ca}_3\text{Al}_2(\text{SiO}_4)_{3-x}(\text{OH})_{4x}$ ( $x=1.5-3.0$ )
Bultfonteinite+	$\text{Ca}_2\text{SiO}_2(\text{OH},\text{F})_4$
Lévyne+	$(\text{Ca},(\text{Na},\text{K})_2)\text{Al}_2\text{Si}_4\text{O}_{12}\cdot 6\text{H}_2\text{O}$
Hillebrandite+	$\text{Ca}_2\text{SiO}_3(\text{OH})_2$
Uranophane	$\text{Ca}(\text{UO}_2)_2(\text{SiO}_3(\text{OH})_2\cdot 5\text{H}_2\text{O})$
Birunite*	$\text{Ca}_{15}(\text{CO}_3)_{5.5}(\text{SiO}_3)_{8.5}\text{SO}_4\cdot 15\text{H}_2\text{O}$
CSH(I) hydrogel*	amorphous Ca:Si = 0.8-1.5 <sup>[4]</sup>
CSH(II) hydrogel*	amorphous Ca:Si = 1.5-2 <sup>[4]</sup>
CSH hydrogel*	amorphous, undefined/variable Ca:Si = <0.8 <sup>[4]</sup>
Tacharanite*	$\text{Ca}_{12}\text{Al}_2\text{Si}_{18}\text{O}_{15}(\text{OH})_2\cdot 3\text{H}_2\text{O}$
CASH hydrogels*	Highly variable compositions between tacharanite and zeolite compositions
CSH-U <sup>+6</sup> phase+	$(\text{CaO})_3(\text{UO}_3)_2(\text{SiO}_2)_{2.5}\cdot 6\text{H}_2\text{O}$ (Unknown)
<b><u>ZEOLITE MINERALS</u></b>	
Chabazite+	$(\text{Ca},(\text{Na},\text{K})_2)(\text{AlSi}_2\text{O}_6)\cdot 6\text{H}_2\text{O}$
Phillipsite+	$\text{KCa}(\text{Al}_3\text{Si}_5\text{O}_{16})\cdot 6\text{H}_2\text{O}$
Mesolite+	$\text{Na}_2\text{Ca}_2(\text{Al}_6\text{Si}_9\text{O}_{30})\cdot 8\text{H}_2\text{O}$
Clinoptilolite+	$(\text{Na},\text{K},\text{Ca})_{2-3}\text{Al}_3(\text{Al},\text{Si})_2\text{Si}_{13}\text{O}_{36}\cdot 12\text{H}_2\text{O}$
Mordenite*	$\text{CaNa}_2\text{K}_2\text{Al}_2\text{Si}_{10}\text{O}_{24}\cdot 7\text{H}_2\text{O}$
Dachiardite*	$(\text{CaNa}_2\text{K}_2)_5\text{Al}_{10}\text{Si}_{38}\text{O}_{96}\cdot 25\text{H}_2\text{O}$
Henlandite*	$(\text{CaNa}_2)\text{Al}_2\text{Si}_7\text{O}_{18}\cdot 6\text{H}_2\text{O}$
Epistilbite*	$\text{Ca}_3\text{Al}_6\text{Si}_{18}\text{O}_{48}\cdot 16\text{H}_2\text{O}$
Yugarawaralite*	$\text{Ca}_2\text{Al}_4\text{Si}_{12}\text{O}_{32}\cdot 8\text{H}_2\text{O}$
Laumontite*	$\text{Ca}_4\text{Al}_8\text{Si}_{16}\text{O}_{49}\cdot 16\text{H}_2\text{O}$
Wairakite*	$\text{Ca}_4\text{Al}_{16}\text{Si}_{32}\text{O}_{96}\cdot 16\text{H}_2\text{O}$
Leonhardite*	$\text{Ca}_4(\text{Al}_8\text{Si}_{16}\text{O}_{48})\cdot 14\text{H}_2\text{O}$
<b><u>CLAY MINERALS</u></b>	
Volkonskoite+*#	$\text{Ca}_{0.3}(\text{Cr},\text{Mg},\text{Fe})_2((\text{Si},\text{Al})_4\text{O}_{10})(\text{OH})_2\cdot 4\text{H}_2\text{O}$
Montmorillonite- Cr-smectite SS+#	$\text{Ca}_{0.3}(\text{Al},\text{Cr},\text{Mg},\text{Zn})_2((\text{Si},\text{Al})_4\text{O}_{10})(\text{OH})_2\cdot 4\text{H}_2\text{O}$
Kaolinite+	$\text{Al}_2\text{Si}_2\text{O}_5$
Palygorskite+	$(\text{MgAl})_2\text{Si}_4\text{O}_{10}(\text{OH})_{24}\cdot \text{H}_2\text{O}$
Illite+	$\text{K}_{0.8}(\text{Al}_{3.8}\text{Mg}_{0.2})(\text{Si})_4\text{O}_{10}(\text{OH})_2$
Chlorite+	$\text{Mg}_3(\text{OH})_6\cdot \text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$
Antigorite/Chrysotile+	$\text{Mg}_3\text{Si}_2\text{O}_5$
<b><u>OTHER PHASES</u></b>	
Apophyllite+*	$\text{KCa}_4\text{Si}_8\text{O}_{20}(\text{OH},\text{F})\cdot 8\text{H}_2\text{O}$ (K,F-rich)
Ca-Cr-silicate hydrogel*	unidentified and undefined
<b><u>URANIUM MINERALS</u></b>	
Carnotite+	$\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2\cdot 3\text{H}_2\text{O}$
Tyuyamunite+	$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2\cdot 5\cdot 8\text{H}_2\text{O}$
Sr-rich tyuyamunite+	$(\text{Ca},\text{Sr})(\text{UO}_2)_2(\text{VO}_4)_2\cdot 6(\text{H}_2\text{O})$
Metatyuyamunite+	$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2\cdot 3\cdot 5\text{H}_2\text{O}$
Strelkinite+	$\text{Na}_2(\text{UO}_2)_2(\text{VO}_4)_2\cdot 6(\text{H}_2\text{O})$
Tyuyamunite –Strelkinite SS+	$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2\cdot 5\cdot 8\text{H}_2\text{O} -$

Autunite+  
X-Phase+



### **References :**

1. *Abdul-Jaber, Q. and Khoury H.N. (1998):* Unusual mineralization in the Maqarin area (north Jordan) and the occurrence of some rare minerals in the marbles and the weathered rocks., N. Jb. Geol. Palaeont. Abh. 208, 603-629, Stuttgart.
2. *Alexander, W. R. (Ed) (1992):* A natural analogue study of the Maqarin hyperalkaline groundwaters. *Phase I. Nagra Technical Report, NTB 91-10, Nagra, Wettingen, Switzerland.*
3. Britvin, S., Murashko, M., Vapnik, Y., Polekhovskiy, Y. & Krivovichev, S. (2015). Earth's Phosphides in Levant and insights into the source of Archean prebiotic phosphorus. *Sci. Rep.* 5, 8355; DOI:10.1038/srep08355.
4. Eckhardt, F.-J. and W. Heimbach (1963) Ein natürliches Vorkommen von  $\text{CaCrO}_4$  (Chromatit). *Naturwiss.*, 50, 612 (in German).
5. *Elie, M., Techer, I., Trotignon, L., Khoury, H., Salameh, E., Vandamme, D., Boulvais, P. and Fourcade, S. (2007):* Cementation of kerogen-rich marls by alkaline fluids released during weathering of thermally metamorphosed marly sediments. Part II: Organic matter evolution, magnetic susceptibility and metals (Ti, Cr, Fe) at the Khushaym Matruk natural analogue (central Jordan). *Applied Geochemistry*, 22, 1311-1328.
6. *Fleurance, S., Cuney, M., Malartre, M., Reyx, J., (2013).* Origin of the extreme polymetallic enrichment (Cd, Cr, Mo, Ni, U, V, Zn) of the Late Cretaceous–Early Tertiary Belqa Group, central Jordan. *Palaeogeography Palaeoclimatology Palaeoecology* 369, 201–219.
7. *Fourcade, S., Trotignon, L., Boulvais, P., Techer, I., Elie, M., Vandamme, D., Salameh, E., and Khoury, H. (2007):* Cementation of kerogen-rich marls by alkaline fluids released during weathering of thermally metamorphosed marly sediments. Part I: Isotopic (C, O) study of the Khushaym Matruk natural analogue (central Jordan). *Applied Geochemistry*, 22, 1293-1310.
8. Heimbach, W. (1965) Zum Vorkommen von Chromatit,  $\text{CaCrO}_4$ , in Jordanien. *Geologisches Jahrbuch*, 83, 717–724 (in German).
9. *Heimbach W, Rosch H (1980):* Die Mottled Zone in Central Jordanian. *Geol Jb B* 40:3–17.
10. *Hauff, P.L., E.E. Foord, S. Rosenblum, and W. Hakki (1983):* Hashemite,  $\text{Ba}(\text{Cr}, \text{S})\text{O}_4$ , a new mineral from Jordan. *Amer. Mineral.*, 68, 1223–1225.
11. *Khoury, H. N. (1993):* Mineralogy and isotope composition of the bituminous limestone of Maqarin area, Jordan. *Dirasat*, 20B, 2, 63-78.
12. *Khoury, H., (2006):* Industrial rocks and minerals in Jordan (second edition). Publications of the University of Jordan, Amman.
13. *Khoury, H. N. (2012):* Long-Term Analogue of Carbonation in Travertine from Uleimat Quarries, Central Jordan. *Environmental and Earth Science*. 65:1909-1916.

14. *Khoury, H. N., (2014a)*. Importance of clay minerals in Jordan - Case study: Volkonskoite as a sink for hazardous elements of a high pH plume. The Jordan Journal of Earth and Environmental Sciences (JJEES). 6, (Special Publication, 3), 1- 10.
15. *Khoury, H. N., (2014b)*. Geochemistry of surficial uranium deposits from central Jordan. The Jordan Journal of Earth and Environmental Sciences (JJEES). 6, (Special Publication, 3), 11- 22.
16. *Khoury, H. N. (2015)*. Uranium Minerals of Central Jordan (2015). Applied Earth Science (Trans. Inst. Min. Metall. B), VOL 124 NO 2, 104-128.
17. *Khoury, H. N., and Nassir S., (1982a)*: High temperature mineralization in Maqarin area, Jordan. N. Jb. Miner. Abh., 144, 187-213.
18. *Khoury, H. N., Nassir, S., (1982b)*: A discussion on the origin of Daba marble. Dirasat, 9, 55-65.
19. *Khoury H, Mackenzie R, Russell J, Tait J (1984)*: An iron free volkonskoite. Clay Miner 19:43–57.
20. *Khoury, H. N., and Salameh, E., (1986)*: The origin of high temperature minerals from Suweileh area. Dirasat, 13, 261-269.
21. *Khoury, H. N. and Abu-Jayab (1995)*: A short note on the mineral volkonskoite. Dirasat, No 1, 189-198.
22. *Khoury, H., and Al-Zoubi, A. (2014)*: Origin and characteristics of Cr-smectite from Suweileh area, Jordan. Applied Clay Science, 90, 43–52.
23. *Khoury, H. N., salameh, E. M. and Clark I. D. (2014)*: Mineralogy and origin of surficial uranium deposits hosted in travertine and calcrete from central Jordan. *Applied Geochemistry*, 43, 49–65.
24. *Khoury, H., Sokol, E., and Clark, I. D. (2015a)*: Calcium uranium oxides from central Jordan: associations, chemistry, and alteration products. The Canadian Mineralogist, Can Mineral 53:61-82, DOI: 10.3749/canmin.1400071.
25. *Khoury, H.N., Sokol, E.V., Kokh, S.N., Seryotkin, Y.V., Nigmatulina, E.N., Goryainov, S.V., Belogub, E.V. and Clark, I.D. (2015b)*: Tululite, IMA 2014-065. CNMNC Newsletter No. 23, February 2015, page 53; Mineralogical Magazine, 79, 51-58.
26. *Khoury, H., Sokol, E., Kokh, S., Seryotkin, Y., Kozmenko, O., Goryainov, S., Clark, I. (2016a)*: Intermediate Members of the Lime-Monteponite Solid Solutions ( $\text{Ca}_{1-x}\text{Cd}_x\text{O}$ ,  $x = 0.36-0.55$ ): Discovery in Natural Occurrence. American Mineralogist, Volume 101, pages 146–161.
27. *Khoury, H., Sokol, E., Kokh, S., Seryotkin, Y., Nigmatulina, E., Goryainov, S., Belogub, E., Clark, I. (2016b)*: Tululite,  $\text{Ca}_{14}(\text{Fe}^{3+}, \text{Al})(\text{Al}, \text{Zn}, \text{Fe}^{3+}, \text{Si}, \text{P}, \text{Mn}, \text{Mg})_{15}\text{O}_{36}$ : a new Ca zincate-aluminate from combustion metamorphic marbles, central Jordan. Mineralogy and Petrology, Miner Petrol., 110:125–140, DOI 10.1007/s00710-015-0413-3
28. *Khoury, H., Kokh, S., Sokol, E., Likhacheva, A. Seryotkin, Y., Belogub, E. (2016c)*: Ba- and Sr-mineralization of fossil fish bones from metamorphosed Belqa Group sediments, central Jordan, Arabian Journal of Geosciences, 9:461. DOI 10.1007/s12517-016-2503-x.
29. *Linklater, C. M. (Ed) (1998)*: A natural analogue study of cement-buffered, hyperalkaline groundwaters and their interaction with a repository host rock. Phase II. Nirex Safety Assessment Research Programme. Report No.S/98/003. PP 301.

30. Nassir, S., and Khoury, H. N., (1982): Geology, Mineralogy and Petrology of Daba marble, Jordan. *Dirasat*, 9 (1), 107-140.
31. Pitty, A.F. and Alexander, R., (Ed), (2011). A natural analogue study of cement buffered, hyperalkaline groundwaters and their interaction with a repository host rock IV: an examination of the Khushaym Matruk (central Jordan) and Maqarin (northern Jordan) sites. NDA-RWMD Technical Report, NDA, Moors Row, UK.
32. Smellie, J. A. T. (Ed) (1998): A natural analogue study of cement buffered, hyperalkaline groundwater and their interaction with a repository host rock. *Phase III. SKB Technical Report*. TR-98-04. PP401.
33. Sokol, E., Kokh, S., Khoury, H., Seryotkin, Y., Goryainov, S. (2016): Long-term immobilisation of Cd<sup>2+</sup> at the Tulul Al Hammam natural analogue site, central Jordan. *Applied Geochemistry* 70, 43-60. <http://dx.doi.org/10.1016/j.apgeochem.2016.05.002>. <http://dx.doi.org/10.1016/j.apgeochem.2016.05.0020883-2927/>© 2016.
34. Sokol, E., Kozmenko, O., Khoury, H., Kokh, S., Novikova, S., Nefedov, A., Sokol, I., and Zaikin, P. (2017): Calcareous Sediments of the Muwaqqar Chalk Marl Formation, Jordan, as a Potential Precursor of Mississippi Valley-Type Deposits: Mineralogical and Geochemical Evidence. *Gondwana Research* 46, 204–226, <http://dx.doi.org/10.1016/j.gr.2017.03.008>. 1342-937X/© 2017 International Association for Gondwana Research. Elsevier B.V.
35. Stasiak, M., Galuskin, E.V., Kusz, J., Galuskina, I.O., Krzykawski, T., Vapnik, Y., Murashko, M. and Dulski, M. (2016). Qatranaitite, IMA 2016-024. CNMNC Newsletter No. 32, August 2016, page 918; *Mineralogical Magazine*, 80, 915–922.
36. Techer, I., Khoury, H., Salameh, E., Rassineux, F., Claude, C., Clauer, N., Pagel, M., Lancelot, J., Hamelin, B., and Jacquot, E., (2006): Propagation of high-alkaline fluids in an argillaceous formation: Case study of the Khushaym Matruk natural analogue (Central Jordan). *Jour. Of Geoch. Exploration*, 90, 53-67.
37. Wieseman, G., Rosch, H., (1969): Das Apatite-vorkomen von Suweilih bei Amman (Nord Jordanien). *Beit. Geol. Jahrb.* 81, 177–214.