

# Opals: characterization, nomenclature definition and proposal of a new varieties classification following the discovery of new materials in Peru

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This work has been carried out on a vast amount of samples (more than 500). In this summary I will concentrate on some of the analytical methods used on the characterization of 25 out of the Andean common opals recently discovered in Arequipa department (Acari, Peru).

All samples are natural common opal type 1 showing blue-green, pink and ochre colours. X-ray diffraction patterns of rough material correspond to opal-C and opal-CT typologies, with also samples having a pure tridimytic composition. Both X-ray diffraction and IR spectrometry allow detection of phyllosilicate species (sepiolite and palygorskite) in several opal-CT samples.

Common opals having different colours and transparencies can be classified into two classes on the basis of the luster exhibited. Relation between the luster and the presence of phyllosilicate phases inside the opals has been assessed. The Andean common opals with vitreous-dull luster (like porcelain) are both opal-C and CT types that do not contain phyllosilicates, whereas the common opals with greasy-waxy luster (like talc) are opals-CT containing phyllosilicates.

The proposed new nomenclature has been combined with a hierarchical classification.

## 1 Results

Description of physical features, X-ray powder diffraction analyses and IR spectroscopic measurements have been applied to many translucent and opaque volcanic opals coming from Arequipa department (Acari region, Peru). All studied materials can be classified as natural common opal type 1, without play-of-colour and body tone ranging from dark to light. On the basis of the colour tonality, three main type of gems are observable: blue-green, pink and ochre samples.

The blue-green opal are opaque or translucent, with colour changing from yellowish green to pale green and pale blue, but it is also present a translucent emerald green sample. The yellowish green, pale green and green samples show a greasy-waxy luster, whereas the pale blue opals and the emerald green gem exhibit a vitreous-dull luster. The values of the measured specific gravity ( $G$ ) are not in relation with the colour tonality and brightness of opals (Tab 1). A difference among blue-green opals can be observed on the fracture of the rough material, that results splintery for common opals with greasy-waxy luster and conchoidal for opals with vitreous-dull luster.

The pink opal samples are opaque, with colours changing from regular pale pink to veined pink and dark pink. Both greasy-waxy luster and vitreous-dull luster can be observed among the pale pink opals, whereas the greasy-waxy luster characterizes the dark pink samples. As observed for blue-green opals, the measured specific gravity ( $G$ ) cannot be used to discriminate among opals with different visual attribute. Also for the pink opals the fracture of the rough material is different among samples of different brightness, being splintery for pink opals with greasy-waxy luster and conchoidal for pink opals with vitreous-dull luster.

Among the material provided us by the dealer there is a sample showing an ochre tonality and a vitreous-dull luster. The ochre rough materials have a conchoidal fracture, confirming that this physical feature is in relation to the brightness of the gem; actually, also blue-green and pink common opals with vitreous-dull luster exhibit this type of fracture.

The powder diffraction analyses performed are able to classify the blue-green common opals as opal-C and opal-CT (Table 1). Figure 1 reports a selection of the X-ray powder diffraction pattern for blue-green common opals. The pale blue common opals with vitreous-dull luster have the well resolved diffraction patterns of the opal-C type and show clearly the additional peaks at  $d = 3.13 \text{ \AA}$  ( $2\theta = 28.48^\circ$ ) and  $d = 2.84 \text{ \AA}$  ( $2\theta = 31.46^\circ$ ) that characterize only C-type opals [1].

The yellowish green and pale green samples with greasy-waxy luster are opal-CT characterized by poor defined diffraction patterns. The relative ratio between cristobalitic and tridymitic component (Table 1) has been measured on the basis of the  $d$  values of the main diffraction peak; the experimental  $d$  value has been considered as a direct combination between the  $d$  value of pure  $\beta$ -cristobalite ( $d = 4.04 \text{ \AA}$ ,  $2\theta = 21.97^\circ$ ) and that of pure tridymite ( $d = 4.11 \text{ \AA}$ ,  $2\theta = 21.60^\circ$ ; [2]). Noticeably, two pale green common opals have  $d = 4.11 \text{ \AA}$ , i.e. they show the  $d$  of pure tridymite. These latter samples are usually defined as opal-CT because they have a poor defined diffraction pattern.

However, all diffraction patterns of yellowish green and pale green opals-CT with greasy-waxy luster show an easily detectable additional peak at low  $2\theta$  value. This peak can be ascribed to the presence of sepiolite. Therefore, this phyllosilicate specie occurs in all yellowish green, pale green and green common opal-CT samples with greasy-waxy luster whereas it is absent in all pale blue opal-C samples with vitreous-dull luster (Table 1).

Interestingly, the emerald green sample no. 5 results an opal-CT without sepiolite (Fig. 2) and, among our blue-green common opals, it is the only opal-CT that exhibits a vitreous-dull luster. This fact allows us to propose that the appearance of a vitreous-dull luster in blue-green common opals is not related to the different type of residual crystallized silica, and then to different volcanic environments of formation, but it is related to the absence of sepiolite, that occurs for all opal-C samples but also for the emerald green opal-CT no. 5.

The powder diffraction analyses of pink common opals (Fig. 3) allow to detect both opal-C and opal-CT types (Table 1). In particular, pink and dark pink common opals with greasy-waxy luster are all opal-CT whereas pale pink opals are opal-C if they exhibit a vitreous-dull luster and opal-CT if they exhibit a greasy-waxy luster. From the  $d$  value of the strongest peak results that none of the pink opal-CT samples has a 100% tridymitic content.

As in blue-green opals, weak diffraction peak of quartz is often present, whereas the diffraction patterns of all pale pink and dark pink opal-CT with greasy-waxy luster show several additional peaks related to the presence of palygorskite; it is not present in pale pink opal-C samples with vitreous-dull luster.

Also for pink common opals result that the luster exhibited is vitreous-dull in absence of phyllosilicate and greasy-waxy in presence of palygorskite. However, palygorskite occurs in all opal-CT samples and the impossibility to observe the luster of a pink opal-CT without phyllosilicate does not allow to substantiate the relation between the type of the luster and the presence of phyllosilicates inside opals.

The XRD study performed on the ochre sample no. 25 allowed us to characterize the ochre opal as a opal-CT without phyllosilicate species. The experimental X-ray powder diffraction pattern is shown on Figure 2 and the availability of a further opal-CT sample that exhibits a vitreous-dull luster confirms that this type of luster can be exhibited also by opal-CT of various colour when phyllosilicates are absent. Actually, among our common opals, the emerald green sample no. 5 and the ochre sample no. 25, both with vitreous-dull luster, are the only two opals-CT free in phyllosilicates

The spectroscopic study performed on several blue-green opal samples reveals that spectra of samples classified as common opal-C by X-ray diffraction study are characterized by a characteristic strong peak at  $622 \text{ cm}^{-1}$  and also by weak bands at  $1200 \text{ cm}^{-1}$  belonging to well-crystallized  $\beta$ -cristobalite [3-5], (Fig. 4). Moreover, in all of the blue-green opal-CT samples that exhibit greasy-waxy luster can be observed additional absorption bands at 3685, 3567, 3248 (weak), 880 and  $691 \text{ cm}^{-1}$  of the sepiolite [5]. Only the emerald green common opal no. 5 shows an absorption spectra of opal-CT samples in which the characteristic bands of sepiolite are absent. This absorption spectrum is reported on Figure 5 whit that of the ochre sample no. 25, the other opal-CT with vitreous-dull luster.

**Table 1:** Optical and physical features of studied rough materials of Andean common opals (samples with \* on the IR column have been used for spectroscopic study).

No.	Tonality	Luster <sup>1</sup>	G	Fract. <sup>2</sup>	Type	$d_{I_{max}}$ (Å) <sup>3</sup>	Content <sup>4</sup> (%)	Phyllo. <sup>5</sup>	IR
1	Yellowish green	GW	1.98	Splint.	CT	4.10	14C 86T	Sep	
2	Pale green	GW	2.16	Splint.	CT	4.09	29C 71T	Sep	*
3	Pale green	GW	2.00	Splint.	CT	4.11	100 T	Sep	*
4	Green	GW	1.98	Splint.	CT	4.11	100 T	Sep	
5	Emerald green	VD	2.05	Conch.	CT	4.08	43C 57T	none	*
6	Pale blue	VD	2.11	Conch.	C	4.05	-	none	
7	Pale blue	VD	2.16	Conch.	C	4.04	-	none	*
8	Pale blue	VD	2.15	Conch.	C	4.05	-	none	
9	Pale blue	VD	2.10	Conch.	C	4.05	-	none	*
10	Pale pink	GW	2.25	Splint.	CT	4.10	14C 86T	Pal	
11	Pale pink	VD	2.13	Conch.	C	4.04	-	none	*
12	Pale pink	VD	2.12	Conch.	C	4.04	-	none	*
13	Pale pink	VD	2.08	Conch.	C	4.04	-	none	
14	Pale pink	VD	2.16	Conch.	C	4.05	-	none	
15	Pale pink	GW	2.07	Splint.	CT	4.08	43C 57T	Pal	
16	Pink	GW	2.09	Splint.	CT	4.10	14C 86T	Pal	
17	Pink	GW	n.d.	Splint.	CT	4.09	29C 71T	Pal	*
18	Dark pink	GW	2.25	Splint.	CT	4.07	57C 43T	Pal	*
19	Dark pink	GW	2.16	Splint.	CT	4.08	43C 57T	Pal	*
20	Dark pink	GW	n.d.	Splint.	CT	4.07	57C 43T	Pal	
21	Dark pink	GW	n.d.	Splint.	CT	4.10	14C 86T	Pal	
22	Dark pink	GW	2.18	Splint.	CT	4.07	57C 43T	Pal	*
23	Dark pink	GW	2.37	Splint.	CT	4.06	72C 28T	Pal	
24	Veined pink	GW	2.16	Splint.	CT	4.10	14C 86T	Pal	
25	Pale ochre	VD	2.01		CT	4.08	43C 57T	none	*

<sup>1</sup> type of luster: GW = greasy-waxy; VD = vitreous-dull.  
<sup>2</sup> type of fracture: Splint = splintery; Conch. = conchoidal.  
<sup>3</sup> value of  $d$  (Å) for the main diffraction peak.  
<sup>4</sup> content of cristobalitic (C) and tridymitic (T) component from the value of  $d_{I_{max}}$ .  
<sup>5</sup> type of phyllosilicate present: Sep = sepiolite, Pal = palygorskite.

As far as absorption spectra of pink common opals are concerned, two categories of spectra can be observed and have been reported on Figure 6. The first category comprises common pale-pink opals classified as opal-C by X-ray diffraction study; their spectra are characterized by the presence of the peak at  $622\text{ cm}^{-1}$  (strong) and  $1200\text{ cm}^{-1}$  (weak) related to the presence of  $\beta$ -cristobalite. The second category of spectra is shown both by pale-pink opals and dark-pink opals described as opal-CT samples by X-ray diffraction study. Absorption spectra of pink opal-CT do not show the cristobalitic absorption bands whereas they present additional absorption bands due to the presence of the palygorskite mineral specie: these bands occur at  $3615$ ,  $3544$  and  $3273$  (weak)  $\text{cm}^{-1}$ , related to crystal water, and at  $985$ ,  $912$  and  $647\text{ cm}^{-1}$ , ascribed to lattice vibrations [2, 5-6].

Noticeably, also the IR spectroscopy shows that the ochre opal no.25 with vitreous-dull luster exhibits the infrared spectrum of an opal-CT without any phyllosilicate phases (Fig. 5).

## 1.1 Discussion

The experimental study that we have performed can be used to found the relations between the colour of common opals from Peru and the presence of phyllosilicate species inside opals.

Actually, in the emerald green and in the pale blue common opals, both XRD study and IR analyses confirm that phyllosilicate species are not present. The observed colours should be ascribed to the presence of chemical constituent into opals and, in general,  $\text{Cu}^{2+}$  ions have been considered as the responsible for the blue-green colour [6]. On the contrary, a phyllosilicate specie (sepiolite) occurs in pale green and yellowish green common opals and the observed colour tonality should be related to the presence of this specie. Sepiolite has been suggested as responsible of yellow-pink colour because it can fix organic phases (carotenoids and quinones) having a pink colour [2,6]. However, our common opals containing sepiolite exhibit a greenish and a yellowish green tonalities that should originate from a mixture of the colour due to sepiolite (pink) and the colour due to chemical constituent (blue).

As far as the pink common opal is concerned, the presence of palygorskite has been related to the pink colour in common opals because also this phyllosilicate specie can fix biogenic phases into its crystal structures (carotenoids and quinones) that act as natural pigments for the pink colour [2,6]. Therefore, palygorskite is the most probable cause of colour for our dark pink common opals.

Finally, the pale ochre common opal is free in phyllosilicates, then their colour tonality should be ascribed to chemical constituents responsible for the ochre tonality.

Opals having vitreous-dull luster (i.e. without phyllosilicates) are all the well crystallized pale blue and pale pink opal-C type, but also the emerald green and the ochre opal. The occurrence of these two opal-CT samples with vitreous-dull luster makes clear that the type of luster is mainly related to the presence of phyllosilicates inside opals and non to the degree of crystallinity (i.e. the environment of formation) of opals.

The XRD study shows that common opals from Acari are accurately described as a continuous series extending from the cristobalitic term (opal-C) towards tridymitic end-member with the most common intermediate composition of opal-CT, in agreement with the possible compositional variation for opals [8]. However, the pure tridymitic terms have diffraction patterns very similar to those of the opal-CT samples: they differ only in the  $d$  value of the main diffraction peak. Therefore, identification of opal-T is hard to be made by observing the general features of the diffraction patterns and the usual two categories of opal (C and CT type) are more than suitable to describe the X-ray diffraction features of Andean opals. The absence of opal-A terms is coherent with the volcanic origin of Andean opals.

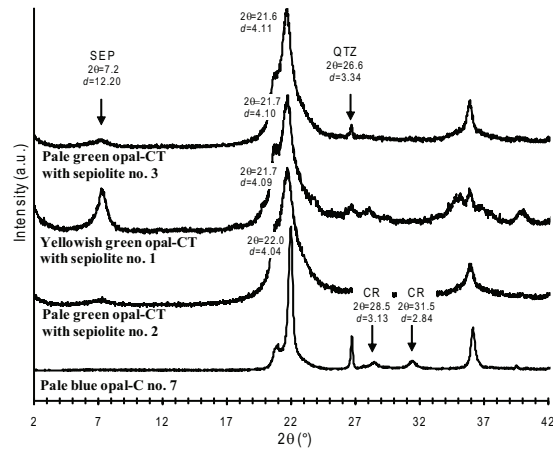
For the proposal of a new nomenclature I have considered all the opal typologies available (“play of color” from Australia, “fire” from Brasil and Mexico, common from Italy, boulder and xyloid) already analysed with the techniques above described along with some others omitted for the sake of brevity in this summary (i.e. Raman spectrometry, LA-ICP-MS, SEM).

The new proposed classification is founded on specific nomenclature principles i.e. the abolition of geographic denominations, the creation of a hierarchy with the same weight for material groups with alike characteristics.

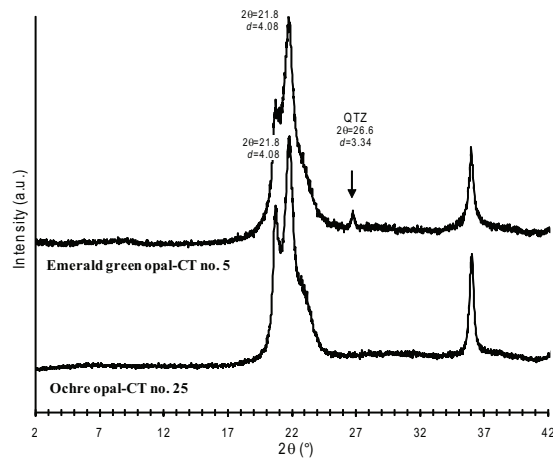
Some determinate taxa have been used such as the subgroup, the variety, the subvariety and the type.

It's a classification with an open scheme that can be completed with the advent of the new materials or can be corrected, extended, or improved within the same framework.

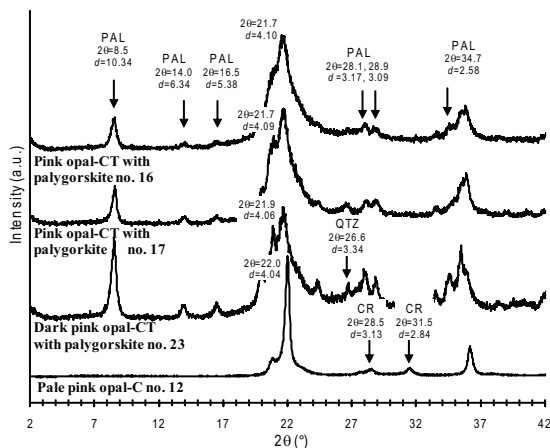
The opal mineral species has been subdivided in two subgroups: non crystalline opals and paracrystalline opals. They are divided in six varieties: “noble” and “ice opal” (for the non crystalline opals); “fire”, “confetti”, “wax”, “cat eye” opal (for the paracrystalline opals). The groups are divided into 43 subvarieties and 140 types. Opals in heterogeneous materials have been divided in two categories: opals with fossils and biogenic opals.



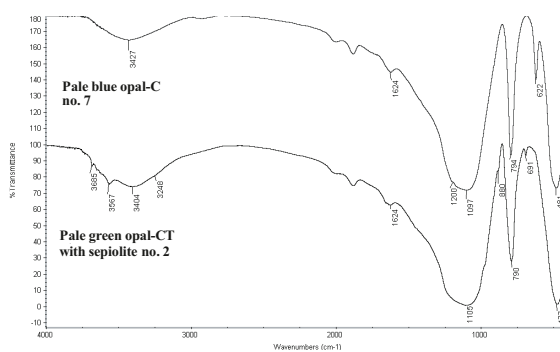
**Fig. 1:** The X-ray diffraction patterns of blue-green common opal allow to detect the presence of both opal-C and opal-CT samples (the sample numbers are those reported on table 1). Position of peaks used to identify the presence of sepiolite (SEP) and quartz (QTZ) are indicate by arrows, with the corresponding  $2\theta$  ( $^\circ$ ) and  $d$  ( $\text{\AA}$ ) values. Also the positions of the two cristobalitic peaks (CR) that characterize C-type opal are shown. The observed  $2\theta$  ( $^\circ$ ) and  $d$  ( $\text{\AA}$ ) values for the principal diffraction peak of opals are also shown. Sample no. 2 and no. 7 have been used also for IR spectroscopy.



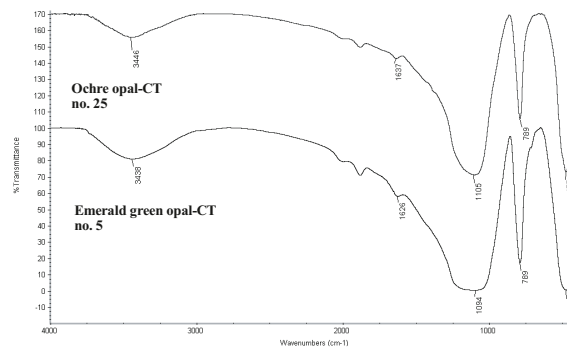
**Fig. 2:** The X-ray diffraction patterns of the two opals-CT that do not contain phyllosilicates and exhibit a vitreous-dull luster: the ochre opal-CT no. 25 and the emerald green opal-CT no.5. The observed  $2\theta$  ( $^\circ$ ) and  $d$  ( $\text{\AA}$ ) values for the principal diffraction peak of opals are shown. Only an additional peak related to the presence of quartz occurs. Both samples have been used also for IR spectroscopy.



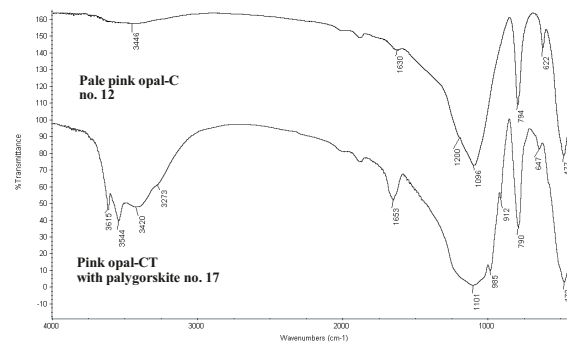
**Fig. 3:** The X-ray diffraction patterns of pink common opal allow to detect the presence of both opal-C and opal-CT samples (the sample numbers are those reported on table 1). Position of peaks used to identify the presence of palygorskite (PAL), cristobalite (CR) and quartz (QTZ) are indicated by arrows, with the corresponding  $2\theta$  ( $^\circ$ ) and  $d$  ( $\text{\AA}$ ) values. The observed  $2\theta$  ( $^\circ$ ) and  $d$  ( $\text{\AA}$ ) values for the principal diffraction peak of opals are also shown. Sample no. 12 and no. 17 have been used also for IR spectroscopy.



**Fig. 4:** FTIR spectra of a pale blue opal-C sample and of a pale green opal-CT sample with sepiolite. The peaks belonging to  $\beta$ -cristobalite (at  $622$  and  $1200 \text{ cm}^{-1}$ ) are absent in the opal-CT sample in which occur absorption bands due to sepiolite (at  $3685$ ,  $3567$ ,  $3248$ ,  $880$  and  $691 \text{ cm}^{-1}$ ).



**Fig. 5:** FTIR spectra of the emerald green opal-CT no. 5 and of the ochre opal-CT no. 25 from Peru. The spectra show similar features, without absorption peaks due to  $\beta$ -cristobalite and to phyllosilicate species. The absence of any phyllosilicates allows exhibition of a vitreous-dull luster for both samples.



**Fig. 6:** FTIR spectra of a pale pink opal-C sample and of pink opal-CT sample with palygorskite. The peaks belonging to  $\beta$ -cristobalite (at 622 and 1200  $\text{cm}^{-1}$ ) are absent in the opal-CT sample in which occur absorption bands due to palygorskite (at 3615, 3544, 3273, 985, 912 and 647  $\text{cm}^{-1}$ ).

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