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STRUCTURE AND SUBSTITUTIONS IN FLUORAPATITE

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Abstract

Fluorapatite, $Ca_{10}(PO_4)_6F_2$. is a widely spread form of calcium phosphate present particularly in biological material. Human hard tissues contain crystals structurally related to apatite. Fluoride can be found in various natural sources and is also used for its beneficial action in caries prevention. Fluorapatite belongs to the spatial group $P6_3/m$ (C_{6h}^2) and consists of 3 ions: F^-, Ca^{2+}, PO_4^{3-}. In the present paper, we have carried out a crystallographic study of the fluorapatite structure and of the changes induced by the substitutions. The fluorapatite structure and the presence of a large number of ionic bonds make fluorapatite a very suitable host for many substitutents, some of them harmless for the human organism, some not. According to the substitution site, we can describe four types of substitution. The F^- substitution, also called Type A substitution, is the main one, and the best known. Only the Ca^{2+} substitution implies changes in the crystal structure. However, some questions remain, in particular for the PO_4^{3-} substitution, which is the main substitution present in the biological calcium phosphates.

Key Words: Apatite structure, space group, point group, substitution, fluoride.

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Introduction

The main components of the apatite family are hydroxyapatite (OHAp, $Ca_{10}(PO_4)_6(OH)_2$), chlorapatite (ClAp, $Ca_{10}(PO_4)_6Cl_2$), carbonated apatites and fluorapatite (FAp, $Ca_{10}(PO_4)_6F_2$). For the latter component, several applications in different areas are known. The existence of several natural minerals containing this component (e.g., Durango, Mexico; Quebec, Canada; New Mexico or Connecticut, USA; Epirus, Greece) (Bale, 1940; Hendricks *et al.,* 1932; Sudarsanan *et al.,* 1972) has led to their use in many applications. There are several methods for synthesis, which allows control of stoichiometry and/or morphology of the synthesized calcium phosphate (Elliot, 1998). In addition, FAp has been used in phosphorus chemistry, as a catalyser or a H_3PO_4 source (this represents 75% of natural apatite use), but also in the area of solid-state laser hosts (rare-earth doped FAp), and in geology as a probe of phosphorus activity in hydrothermal, metamorphic or magmatic processes. FAp is also the main calcium phosphate used in phosphated fertilisers. However, its first industrial use, in a Sb- or Mn-substituted form remains the production of fluorescent lamps (estimated to 10 tons per day in 1991) (DeBoer *et al.,* 1991; Fleet and Pan, 1997; Hughes *et al.,* 1991; Miyake *et al.,* 1986; Suitch *et al.,* 1985). Calcium apatites are also important in biology, because they form the mineral part of bone and teeth, and take part in the mineralization process. FAps are used as biocompatible materials for bone replacement and coating of bone prostheses.

One of the components of FAp is fluoride, which is often used therapeutically in order to prevent caries. In nature, fluoride can be found in soils, in minerals such as fluorine, hornblende, pegmatite, and FA. Due to erosion, fluoride salts are also present in the atmosphere. The atmospheric concentration of fluoride salts depends on the presence of fluoride in the environment. Therefore, it is a function of the presence of fluoride in soils or in industrial waste. Fluoride is also present in water, especially in the oceans, or near mountainous or sedimentary areas. Water is also used as a medium of caries prevention politics, and so represents the main source of fluoride in our alimentation. We also can find natural fluoride in some foods, especially in plants, at different concentrations independent of the soil concentration (Plouvier, 1997). All fluoride ingested is first taken up by the circulation, and then in hard tissues (such as bone or dentin). The fixation of fluoride by bone and tooth depends on the supply of fluoride and the age of the subject. Bone is responsible for the homeostasis of fluoride in the organism. Fluoride is excreted by the kidneys, *via* a passive diffusion mechanism.

This excretion represents 40 to 60% of the fluoride ingested.

Fluoride plays an important role in caries prevention: it increases the resistance of the mineral to acid dissolution, and decreases mineral solubility (Aoba, 1997; Featherstone, 1994). By substituting for the OH^- ion in the apatite molecule during the development phase of dentin and enamel, fluoride fixes calcium, provides increased stability to the mineral structure, and promotes remineralization (Aoba 1997; Ingram, 1990; Triller 1998).

Moreover, FAp is a suitable host for various substituents that could modify its physicochemical and/or biological properties. Most of these substituents are harmless, and sometimes necessary for the organism, but some of them could be very dangerous; they could be toxic or cause irreversible modifications of FAp.

All these applications promote scientific interest in this compound. FAp is one of the first apatites of which the structure was described (Mehmel, 1932; Naray-Szabo, 1930), and is considered as a reference model to describe other apatites (Elliot, 1994).

The FAp space group $P6_3/m$ (or C_{6h}^2 in the Schöenflies notation) describes the general atomic positions inside its unit cell according to the S.I. and hence permits the construction of the position of the atoms of the unit-cell starting from four ions only: F^-, Ca_I^{2+}, Ca_{II}^{2+} and PO_4^{3-}. The knowledge of such symmetries is not only useful for understanding the very structure of FAp but also for the detection of apatite phases and of the structural modifications induced by substitutions and hence for the understanding of the behaviour of biological and synthetic calcium phases. In the present paper, we have carried out a graphical construction of all the atoms of the FAp unit-cell using the symmetry operators of the $P6_3/m$ space group.

Crystallographic Data

The FAp ionic crystal belongs to the space group $P6_3/m$ (C_{6h}^2 in the Schöenflies notation), and its parameters are $a = b = 9.462$ Å and $c = 6.849$ Å, $a = b = 90°$, $g = 120°$ (Hughes *et al.,* 1989). The main symmetry elements are (Naray-Szabo, 1930):

Atom	Symmetry site	Crystallographic data		
F	$\bar{6}$ (C_{3h})	0	0	¼
Ca(I)	3 (C_3)	$^1/_3$	$^2/_3$	0.00010
Ca(II)	m (C_s)	-0.0071	0.2423	¼
P	m (C_s)	0.3690	0.3985	¼
O(I)	m (C_s)	0.4849	0.3273	¼
O(II)	m (C_s)	0.4667	0.5875	¼
O(III)	1 (E)	0.2575	0.3421	0.0705

Table 1: Positions of non-equivalent atoms of FAp. (Hughes *et al*. 1989).

- A mirror plane, perpendicular to the *c*-axis, at z = ¼,
- A screw axis 6_3 at the unit-cell origin, parallel to the *c*-axis, and associated with an inversion centre at (0 ; 0 ; 0),
- Three screw axes 2_1 parallel to the *c*-axis, at the centre of the unit-cell in (½; ½; z), (½; 0; z) and (0; ½; z). Each axis is associated with an inversion centre (½ ;½ ;0), (½ ;0 ;0), et (0 ;½ ;0) respectively,
- Two improper rotation axes $\bar{6}$, parallel to the *c*-axis, at ($^1/_3$; $^2/_3$; z) and ($^2/_3$; $^1/_3$; z).

A FAp unit-cell contains 7 non-equivalent atoms: F, Ca_I, Ca_{II}, P, $O_{(I)}$, O_{II} and O_{III} (Table 1). To show this property, the FAp chemical formula is written as: $Ca(I)_4Ca(II)_6\,[PO(I)O(II)O(III)_2]_6\,F_2$ which takes into account the 4 non-equivalent ions (Table 2):

- F^-
- PO_4^{3-}
- Ca_I^{2+}
- Ca_{II}^{2+}

As Table 1 shows, the atoms are always described by a site symmetry and a single series of coordinates. All other positions can be found with the different symmetry elements. The O_{III} atom, which is located at (0.3416 ; 0.2568 ; 0.0704) is in a general position with its site symmetry equal to the identity *1(E)*. All the symmetry operations are used to obtain 12 equivalent points.

Atom	Multiplicity and Wyckoff Symbol	Crystallographic data
F	2 *a*	(0 ;0 ; ¼), (0 ;0 ; ¾)
Ca(I)	4 *f*	($^1/_3$;$^2/_3$; z), ($^2/_3$;$^1/_3$; z), ($^2/_3$;$^1/_3$; z+½), ($^1/_3$;$^2/_3$; ½-z)
Ca(II) **P** **O(I)** **O(II)**	6 *h*	(x ; y ; ¼), (1-y; x-y ;¼), (y-x ; 1-x ; ¼), (1-x; 1-y ; ¾) (y ; y-x ; ¾), (x-y ; x ; ¾)
O(III)	12 *i*	(x ; y ; z) (1-x ;1-y ;1-z) (1-x ;1-y ;½+z) (x ; y ; ½-z) (1-y; x-y; z) (y ;y-x ;1-z) (y ;y-x ;½+z) (1-y ; x-y ; ½-z) (y-x; 1-x; z) (x-y ;x ;1-z) (x-y ;x ;½+z) (y-x ; 1-x ; ½-z)

Table 2: Site symmetry of FAp atoms in the space group $P6_3/m$, according to the International Tables of Crystallography (Hann 1993. Schutte *et al*. 1997).

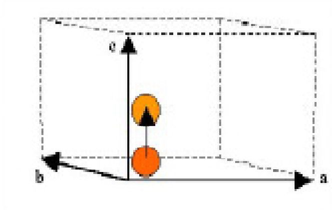
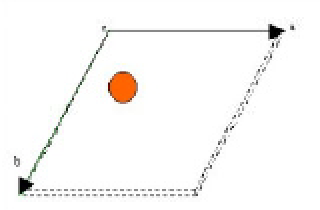
Symmetry opération	Unit-Cell	Coordinates	View [000$\bar{1}$]
m : *mirror symmetry at z = ¼* *(x ;y ;z) → (x ;y ;1/2-z)*		0.3416 ; 0.2568 ; 0.0704 ↓ 0.3416 ; 0.2568 ; 0.4296	

Figure 1: Transformations induced by the mirror plane.

Mirror plane

The mirror plane at z = ¼ transforms the initial point to (x ; y ; ½-z), *i. e.* (0.3416 ; 0.2568 ; 0.0704) to (0.3416 ; 0.2568 ; 0.4296) (Fig. 1).

axis $\overline{6}_3$

The 6_3 axis is located at (0 ; 0 ; z), at the same location as the *c*-axis. The O_{III} atom was submitted to a series of operations, consisting of a 2p/6 rotation and a 3/6 *c* (= ½ *c*) translation. We obtained 6 new points (Fig. 2) :

- (x-y ; x ;½+z) : 0.0848; 0.3416 ;0.5704
- (-y ; x-y;1+z) : -0.2568 ;0.0848 ; 1.0704
- (-x ; -y;1½+z) :-0.3416 ;-0.2568 ;1.5704
- (y-x ;-x ;2+z) :-0.0848 ;-0.3416 ;2.0704
- (y; y-x;2½+z) : 0.2568 ;-0.0848 ;2.5704
- (x; y ;3+z) : 0.3416 ;0.2568 ; 3.0704

The inversion point at the origin of the unit-cell transforms these atoms to 6 new points at (-x' ;-y' ;-z') :

- (-0.0848;-0.3416 ;-0.5704),
- (0.2568 ; -0.0848 ;-1.0704),
- (0.3416 ; 0.2568 ; -1.5704),
- (0.0848 ; 0.3416 ; -2.0704),
- (-0.2568 ; 0.0848 ;-2.5704)
- and (-0.3416;-0.2568 ;-3.0704)

Most of those atoms are outside the FAp unit-cell, but we can find their equivalents inside the unit-cell by lattice translations. So the equivalent positions in the unit-cell are (Fig. 2) :

- (x ; y ;½-z) : 0.3416 ; 0.2568 ; 0.4296
- (x-y;1-x ;½-z): 0.0848;0.6584 ;0.4296
- (1-y ;x-y ;½-z) : 0.7432; 0.0848;0.4296
- (x-y ; x ; 1-z) : 0.0848 ;0.3416 ; 0.9296
- (y ;1-x+y ;1-z) : 0.2568; 0.9152; 0.9296
- (1-x ;1-y ;1-z) : 0.6584; 0.7432 ; 0.9296

$\overline{2}_1$ axis

There are three 2_1 axes, at (½; ½; z), (½ ; 0 ; z) and (0 ; ½ ; z). Each axis submits the atoms to a 2p/2 rotation and a translation of ½ *c*. From the (x ;y ;z) coordinates, we obtained 3 points : (2*½-x ; -y ; ½+z) , (2*½-x; -y ; ½+z) and (-x; 2*½-y ; ½+z) ; *i.e.* (1-x ; 1-y ; z+½), (1-x ; -y ; z+½) and (-x ; 1-y ; z+½). The succession of these operations gives atoms outside the unit-cell, at (x ; y ; 1+z). Moreover, the inversion points at (½ ; ½ ; 0), (½ ; 0 ; 0) and (0 ; ½ ; 0) transform the coordinates to (1-x' ;1-y' ;-z'), (1-x' ; -y' ; -z'), and (-x' ;1-y' ;-z'). Most of the obtained points are outside the unit-cell, but their equivalents can, due to lattice translations, be found within the unit-cell. The new positions of the O_{III} atom are (Fig. 3):

- axis $\overline{2}_1$ at (½; ½; z) : (0.3416; 0.2568 ;-0.5704) ; (0.6584; 0.7432 ;-1.0704)
- axis $\overline{2}_1$ at (½; ½; z) : (0.3416 ; 0.2568 ; -0.5704) ; (0.6584 ;-0.2568 ; -1.0704)
- axis $\overline{2}_1$ at (0 ; ½; z) : (0.3416 ; 0.2568; -0.5704) ; (-0.3416 ; 0.7432; -1.0704)

In the FAp unit-cell, those positions give two equivalent positions (Fig. 3):

- (1-x ; 1-y ; 1-z) : 0.6584 ; 0.7432 ; 0.9296
- and (x ; y ; ½-z) : 0.3416 ; 0.2568 ; 0.4296

axis $\overline{6}$

The unit-cell of the space group $P6_3/m$ has 2 $\overline{6}$ axis at ($^1/_3$; $^2/_3$; z) and ($^2/_3$; $^1/_3$; z). Each axis is in fact a 2p/6 rotation and an n inversion. The inversion centres associated with the *6* axis are :

- ($^1/_3$; $^2/_3$; ¾) for the ($^1/_3$; $^2/_3$; z) axis
- and ($^2/_3$; $^1/_3$; ¼) for the ($^2/_3$; $^1/_3$; z) axis.

The first $\overline{6}$ axis, at ($^1/_3$; $^2/_3$; z), gives the following points (Fig. 4):

- (y-x ;1-x ; 1½-z) : -0.0848 ; 0.6584 ; 1.4296
- (1-y ; x-y ; z) : 0.7432 ; 1.0848 ; 0.0704
- (x ; y ; 1½-z) : 0.3416 ; 0.2568 ; 1.4296
- (y-x ; 1-x ;z) : -0.0848 ; 0.6584 ; 0.0704
- (1-y ; x-y ;1½-z) : 0.7432 ; 1.0848 ; 1.4296
- and (x ;y ;z) : 0.3416 ; 0.2568 ; 0.0704

The second $\overline{6}$ axis at ($^2/_3$; $^1/_3$; z) gives the following points (Fig. 4):

- (1+y-x ;1-x ; ½-z) : 0.9152 ; 0.6584 ; 0.4296
- (1-y ; x-y ; z) : 0.7432 ; 0.0848 ; 0.0704
- (x ; y ; ½-z) : 0.3416 ; 0.2568 ; 0.4296
- (1+y-x ; 1-x ;z) : 0.9152 ; 0.6584 ; 0.0704
- (1-y ; x-y ; ½-z) : 0.7432 ; 0.0848 ; 0.4296
- and (x ;y ;z) : 0.3416 ; 0.2568 ; 0.0704

Equivalent positions

According to the translation due to the crystal lattice, all the previous points have their equivalents in the unit-cell. There are 12 points and their coordinates are (Fig. 2):

- (x ; y ; z) : **0.3416 ; 0.2568 ; 0.0704**

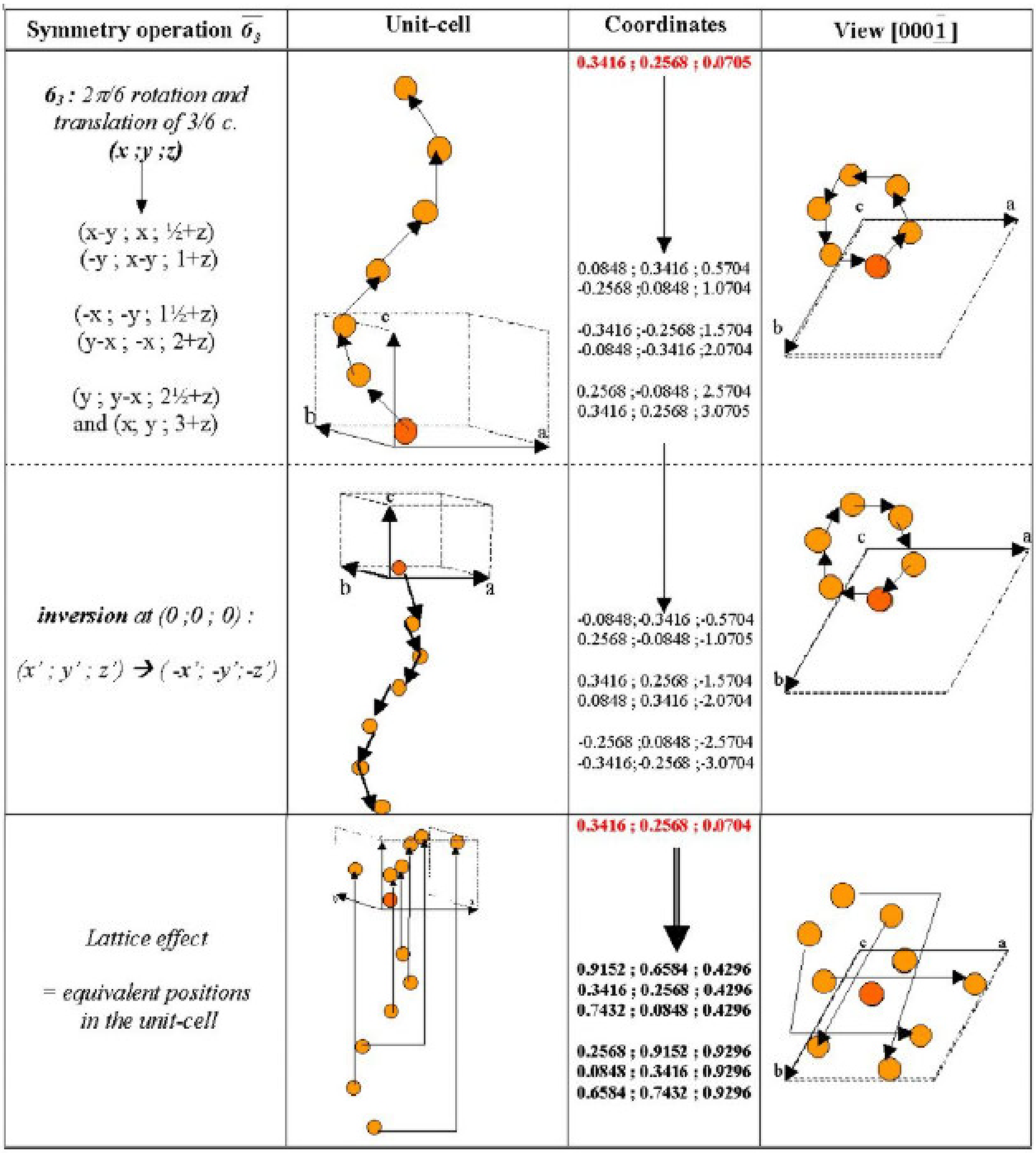


Figure 2: $\overline{6_3}$ symmetry operations.

- (1-y ; x-y ; z) : 0.7432 ; 0.0848 ; 0.0704
- (y-x ; 1-x ; z) : 0.9152 ; 0.6584 ; 0.0704
- (1-x ;1-y ;1-z) :0.6584 ;0.7432 ; 0.9296
- (y ; y-x ; 1-z) : 0.2568 ; 0.9152 ; 0.9296
- (x-y ; x ; 1-z) : 0.0848 ; 0.3416 ; 0.9296
- (1-x ;1-y ;½+z) :0.6584 ;0.7432 ;0.5704
- (y ; y-x ; ½+z) : 0.2568 ;0.9152 ; 0.5704
- (x-y ; x ; ½+z) : 0.0848 ;0.3416 ; 0.5704
- (x ; y ; ½-z) : 0.3416 ; 0.2568 ; 0.4296
- (1-y ;x-y ;½-z) :0.7432 ;0.0848 ; 0.4296
- (y-x ;1-x ;½-z) :0.9152 ;0.6584 ; 0.4296

The other atoms of the FAp molecule are subject to the same symmetry laws as the O_{III} atom. However, they are in special positions, *i.e.,* at the position of one or more symmetry elements. Therefore they are not changed by these symmetry operations and the number of equivalent positions decreases.

P, O_I, O_{II} and Ca_{II} atoms belong to the same point group *m* (C_s), and are located in the same Wickoff position *h*. That means that the same transformations are applied to their coordinates, and hence the description of one atom is enough to find the other atoms. Therefore only the positions of Ca_{II}^{2+} ions, coordinates (0.2416; 0.0071; ¼), are described below. The positions of the other atoms are found with the general coordinates of the equivalent positions.

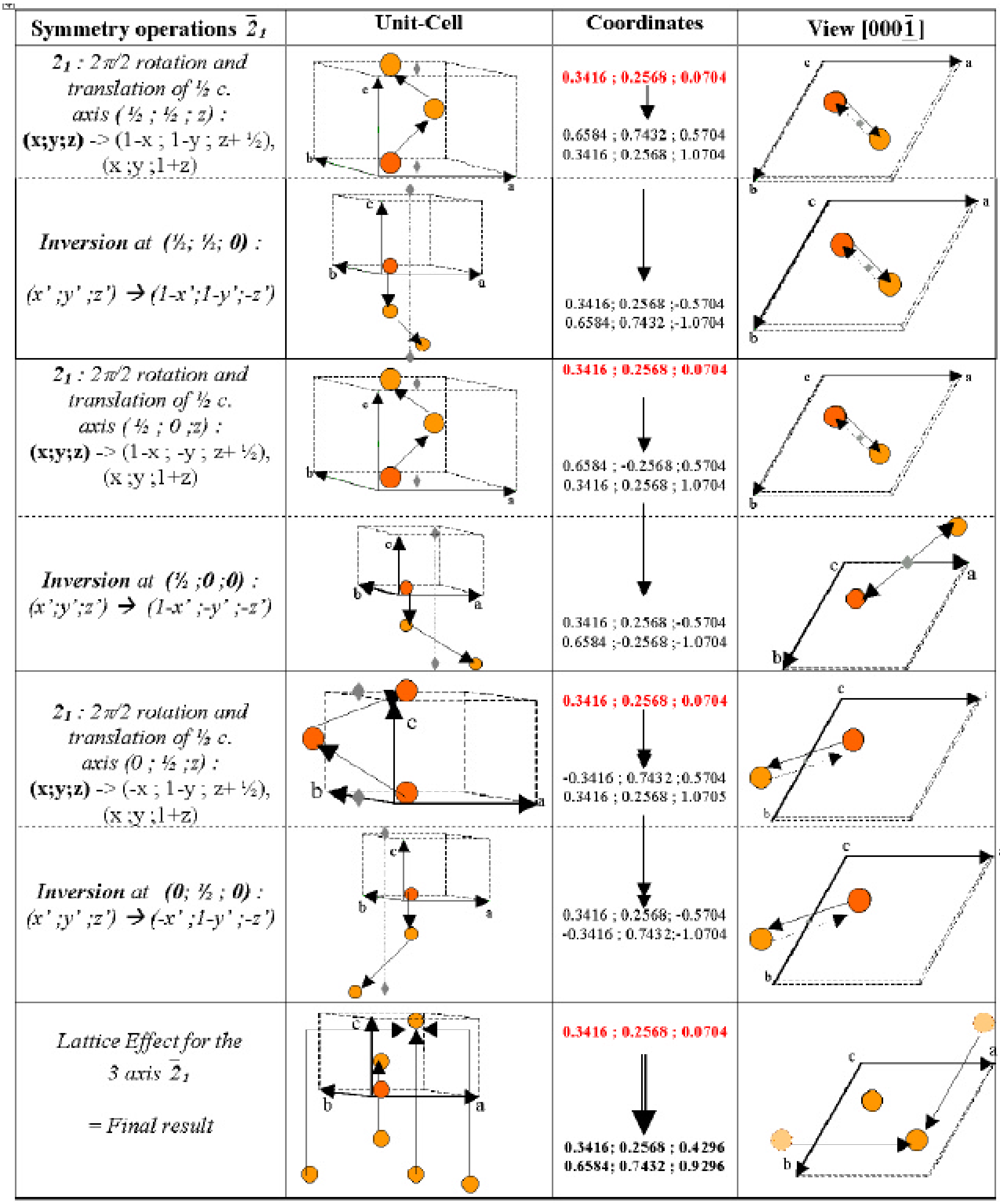


Figure 3: Description of the $\bar{2}_1$ symmetry operations.

mirror plane *m*

The Ca_{II}^{2+} ion, coordinates (0.2416; 0.0071; ¼), and the P, O_I and O_{II} atoms are in the mirror plane, and therefore unaffected by this symmetry operation. However, the other symmetry operations $\bar{6}_3$, $\bar{2}_1$ and $\bar{6}$ axis influence these atoms. Only the positions of the Ca_{II}^{2+} ion are described below.

axis $\bar{6}_3$

According to the 6_3 axis, the Ca_{II}^{2+} ion is influenced by a series of operations composed of a 2p/6 rotation and a translation of 3/6 *c* (= ½ *c*). We obtained 6 new points :

- (x-y ; x ; ½+z) : 0.2345 ; 0.2416 ; ¾
- (-y ; x-y ; 1+z) : -0.0071 ; 0.2345 ;1¼
- (-x ;-y ;1½+z) : -0.2416 ;-0.0071 ;1¾
- (y-x ;-x ; 2+z) : -0.2345; -0.2416 ;2¼,
- (y ; y-x ; 2½+z) : 0.0071 ; -0.2345; 2¾

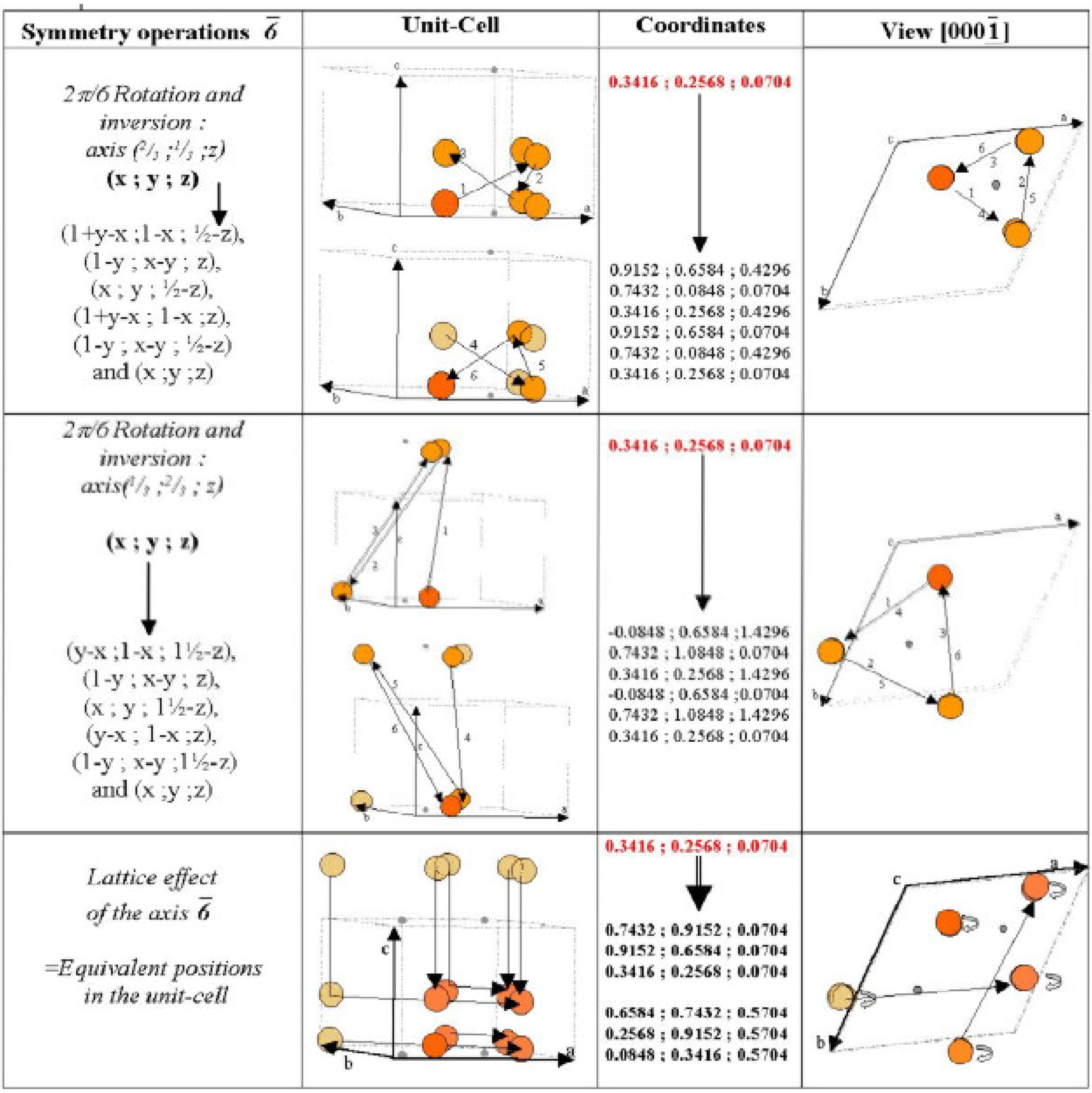


Figure 4: Description of the transformations induced by the $\bar{6}$ axis

- and (x ; y ; 3+z) : 0.2416 ; 0.0071 ; 3¼.

This last point is identical to the (x ; y ; z) point, with a translation of *3c*. The inversion point at the unit-cell origin transforms these atoms to (-x' ;-y' ;-z') :

- (-0.2345; -0.2416 ;-¾),
- (0.0071 ;-0.2345 ;-1¼),
- (0.2416 ;0.0071 ;-1¾),
- (0.2345 ;0.2416 ;-2¼),
- (-0.0071 ; 0.2345;-2¾)
- and (-0.2416 ; -0.0071 ;-3¼).

Most of these points are outside the unit-cell, but their equivalents are found in the unit-cell according to the lattice translations :

- (x ; y ; ¼) : 0.2416; 0.0071; ¼
- (1-(y-x) ;1-x ;¼): 0.7655; 0.7584 ; ¼
- (1-y; x-y; ¼) : 0.9929 ; 0.2345; ¼
- (1-x ; 1-y ; ¾) : 0.7584; 0.9929 ; ¾
- (x-y ; x ; ¾) : 0.2345; 0.2416 ; ¾
- (y ; 1-(y-x) ; ¾) : 0.0071; 0.7655; ¾

axis $\bar{2}_1$

Under the influence of the 3 2_1 axis, the initial point occurs at (1-x ; 1-y ; ½+z), (1-x ; y ; ½+z), and (x ; 1-y ; ½+z), *i.e.* for the Ca_{II}^{2+} ion : (0.7584 ; 0.9929 ; ¾), (0.7584 ; 0.0071 ; ¾) and (0.2416 ; 0.9929 ; ¾) then at (0.2416 ; 0.0071. 1¼). The inversion points at (½ ; ½ ; 0), (½ ; 0 ; 0) and (0 ; ½ ; 0) transform these atoms at (0.2416 ; 0.0071 ;-¾), then at (0.7584 ;-0.0071 ;-1¼), (0.7584 ; 0.9929 ;-1¼), (-0.2416 ; 0.9929;-1¼). By translations, these 3 positions give a unique equivalent in the unit-cell: the position (1-x ; 1-y ; ¾) *i.e.* (0.7584 ; 0.9929 ; ¾).

axis $\bar{6}$

For the operations due to the $\bar{6}$ axis at ($^2/_3$; $^1/_3$; z), the Ca_{II}^{2+} ion (and the P, O_I et O_{II} atoms) reacts only to the inversion in its coordinates x and y because the inversion point is in the same plane as the Ca_{II}^{2+} ion, at ($^2/_3$; $^1/_3$; ¼). The successive rotations do not give 6 points located in 2 triangles at z=¼ and z=¾, but 3 points in a triangle at z=¼ :

- (1-y ; x-y ; ¼) : 0.9929 ; 0.2345 ; ¼
- (1+y-x ; 1-x ; ¼) : 0.7655 ; 0.7584 ; ¼
- (x ;y ; ¼) : 0.2416 ; 0.0071 ; ¼.

The other $\bar{6}$ axis at ($^1/_3$; $^2/_3$; z) has an inversion point at ($^1/_3$;$^2/_3$; ¾) and gives 6 points:

- (y-x;-x ;1½-z) :-0.2345;0.7584;1¼
- (1-y ;x-y ; z) : 0.9929 ;-0.2345 ; ¼
- (x ; y ;1½-z) : 0.2416 ; 0.0071; 1¼
- (y-x ; 1-x ; z) :-0.2345 ;0.7584 ; ¼
- (1-y;x-y ;1½-z) :0.9929;-0.2345;1¼
- and (x ; y ; z) : 0.2416 ; 0.0071 ; ¼.

There are 3 equivalent points in the unit-cell : (x ; y ;¼), (1-(x-y) ;1-x ; ¼) and (1-y ; 1-(x-y) ; ¼), *i.e.* (0.2416 ; 0.0071 ; ¼), (0.7655 ; 0.7584 ; ¼) and (0.9929 ; 0.7655 ; ¼).

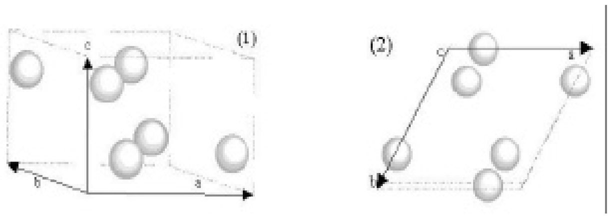


Figure 5: Equivalent positions of the Ca_{II}^{2+} ions. (1) Unit-cell: (2) view [000$\bar{1}$]

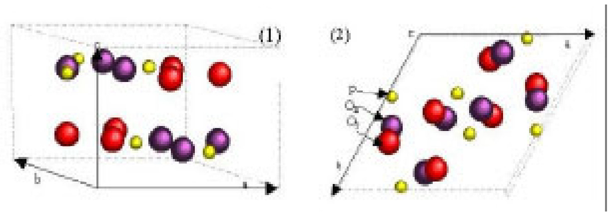


Figure 6: Equivalent positions of the P, O_I and O_{II}. atoms. (1) Unit-cell: (2) view [000$\bar{1}$]

Equivalent positions

These symmetry operations give the same 6 equivalent positions, with identical coordinates (Figs. 5 and 6*):*

- (x ; y ; ¼) : 0.2416; 0.0071; ¼
- (1-y ; x-y ; ¼) : 0.9929 ; 0.2345; ¼
- (y-x ; 1-x ; ¼) : 0.7655; 0.7584 ; ¼
- (1-x ; 1-y ; ¾) : 0.7584; 0.9929 ; ¾
- (y ; y-x ; ¾) : 0.0071; 0.7655; ¾
- and (x-y ; x ; ¾) : 0.2345; 0.2416 ; ¾.

The Ca_I^{2+} ion, coordinates ($^1/_3$;$^2/_3$;0.0011), is located in the symmetry site *3(C$_3$).*

mirror plane *m*

The mirror plane at z=¼ transforms the initial point to (x ; y ; ½-z), *i.e.* ($^1/_3$;$^2/_3$;0.4989).

axis $\overline{6_3}$

Under the influence of the 6_3 axis, the Ca_I^{2+} ion is submitted to a series of operations, consisting of a 2p/6 rotation and a translation of 3/6 *c* (= ½ *c*). We obtain 6 new points :

- (x-y ; x ; ½+z) : -$^1/_3$; $^1/_3$; 0.5011
- (-y ; x-y ; 1+z) : -$^2/_3$; -$^1/_3$; 1.0011
- (-x ; -y ; 1½+z) : -$^1/_3$; -$^2/_3$; 1.5011
- (y-x ; -x ; 2+z) : $^1/_3$; -$^1/_3$; 2.0011
- (y ; y-x ; 2½+z) : $^2/_3$; $^1/_3$; 2.5011
- and (x; y ; 3+z) : $^1/^3$; $^2/_3$; 3.0011.

The inversion point at the origin of the unit-cell transforms these atoms to 6 new points at (-x' ;-y' ;-z'):

- ($^1/_3$; -$^1/_3$; -0.5011)
- ($^2/_3$; $^1/_3$; -1.0011)
- ($^1/_3$;$^2/_3$; -1.5011)
- (-$^1/_3$; $^1/_3$; -2.0011)
- (-$^2/_3$; -$^1/_3$; -2.5011)
- and (-$^1/_3$; -$^2/_3$; -3.0011)

Most of those points are outside the unit-cell, but their equivalents are found in the unit-cell with the lattice translations. Their coordinates are :

- (x ; y ; ½-z) : $^1/_3$; $^2/_3$; 0.4989
- (1-x ; 1-y ; 1-z) : $^2/_3$; $^1/_3$; 0.9989

$\overline{2_1}$ axis

Under the influence of the 2_1 axis, the initial point goes to (1-x ; 1-y ; ½-z), (1-x ; -y ; ½-z), and (-x ; 1-y ; ½-z), *i.e* . ($^2/_3$;$^1/_3$;0.5011), ($^2/_3$;-$^2/_3$;0.5011) and (-$^1/_3$;$^1/_3$;0.5011), then at (x ; y ; 1+z), *i.e.* ($^1/_3$; $^2/_3$; 1.0011). All the inversion points at (½ ; ½ ; 0), (½ ; 0 ; 0) and (0 ; ½ ; 0) give the same point at ($^1/_3$; $^2/_3$; -0.5011).

$\bar{6}$ axis

The Ca_I^{2+} ion is located in the $\bar{6}$ axis, parallel to the *c*-axis at ($^1/_3$; $^2/_3$; z). Therefore it is not affected by the *6* rotation at ($^1/_3$; $^2/_3$; z), but the inversion according to the ($^1/_3$;$^2/_3$, ¾) point gives ($^1/_3$; $^2/_3$; 1.4999), and then ($^1/_3$; $^2/_3$; 0.0011). The other axis, at ($^2/_3$;$^1/_3$; z), gives 6 points : (1+y-x ; 1-x ;½-z), (1-y ; x-y ; z), (x ;y ;½-z), (1+y-x ;1-x ;z), (1-y ;x-y ;½-z), and (x ; y ; z), *i.e.* ($^4/_3$; $^2/_3$; 0.4989), ($^1/_3$;-$^1/_3$;0.0011), ($^2/_3$; $^1/_3$; 0.4989), ($^4/_3$;$^2/_3$; 0.0011), ($^1/_3$; -$^1/_3$; 0.4989) and ($^1/_3$;$^2/_3$; 0.0011).

Equivalent positions

According to the particular coordinates x and y of the Ca_I^{2+}, x = $^1/_3$ and y =$^2/_3$ the different symmetry operations give identical positions. The Ca_I^{2+} ion has 4 equivalent positions (Fig. 7) :

- (x ; y ; z) : $^1/_3$; $^2/_3$; 0.0011
- (1-x ; 1-y ; 1-z) : $^2/_3$; $^1/_3$; 0.9989
- (x ; y ; ½-z) : $^1/_3$; $^2/_3$; 0.4989
- (1-x ; 1-y ; ½+z) : $^2/_3$; $^1/_3$; 0.5011

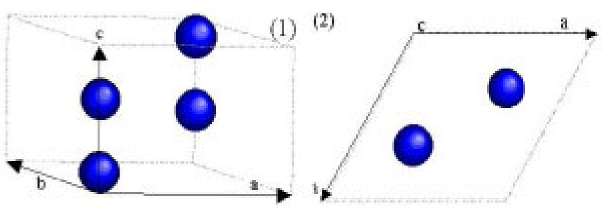


Figure 7: Equivalent positions of the Ca_1^{2+} ion: (1) Unit-cell (2) View [000$\bar{1}$]

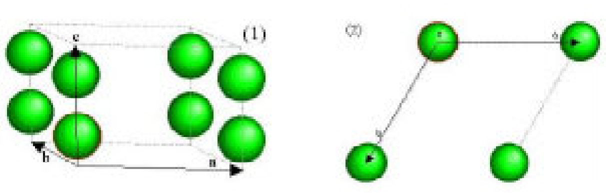


Figure 8: Equivalent positions of the F^- ion: (1) Unit-cell. (2) View [000$\bar{1}$]

The F^- ion, coordinates (0 ; 0 ; ¼), is located in the symmetry sites $\bar{6}(C_{3h})$, and in the mirror plane, on the 6_3 axis at the unit-cell origin. Moreover, its particular coordinates cause it to be unaffected by several symmetry operations.

Mirror plane *m*

The F^- ion is located in the mirror plane at z = ¼. Hence it is not influenced by the mirror symmetry.

$\overline{6_3}$ axis

The presence of the F^- ion on the *c*-axis causes it to be unaffected by the *6* rotation. But the translation of 3/6 *c* due to the 6_3 axis gives the point (0 ;0 ; ¾), then the same at z= 1 ¼, 1 ¾, 2¼, 2 ¾ and 3 ¼. The inversion due to the point (0 ;0 ;0) gives (0 ;0 ;-¾), then z= -1 ¼, -1 ¾, -2¼, -2 ¾ and -3 ¼, which gives by translations in the unit-cell (0 ;0 ; ¼), which is the initial point and (0 ; 0 ; ¾).

$\overline{2_1}$ axis

With the 2_1 axis, the F^- ion is submitted to a 2p/2 rotation and a translation of ½ *c*. Its new positions are :

- (1-x ; 1-y ; ½+z) : 1 ; 1 ; ¾
- (1-x ; -y ; ½+z) : 1 ; 0 ; ¾
- (-x ; 1-y ; ½+z) : 0 ; 1 ; ¾

The succession of this operation goes outside the unit-cell at (x ;y ;1+z), *i.e.* (0 ; 0 ; 1 ¼). The inversion points (½ ; ½ ; 0), (½ ; 0 ; 0) at (0 ; ½ ; 0) transform the coordinates (x' ; y' ; z') to (1-x ;1-y ;-z), (1-x ; -y ; -z), to (-x ;1-y ;-z). Because of the particular coordinates of the F^- ions, this symmetry operation is similar to a transformation of the 3 points to the point (0 ;0 ; ¼), the initial point, then to (1 ;1 ; -¼), (1 ; 0 ; -¼) and (0 ; 1 ; -¼). These 3 last points are equivalent to (0 ;0 ; ¾).

$\bar{6}$ axis

The first $\bar{6}$ axis located at ($^1/_3$; $^2/_3$; z) gives the following points :

- (y-x ;1-x ; 1½-z) : 0 ; 1 ;1¼
- (1-y ; x-y ; z) : 1 ; 0 ; ¼
- (x ; y ; 1½-z) : 0 ; 0 ; 1¼
- (y-x ; 1-x ;z) : 0 ; 1 ;¼
- (1-y ; x-y ;1½-z) : 1 ; 0 ; 1¼
- and (x ;y ;z) : 0 ; 0 ; ¼.

The second $\bar{6}$ axis located at ($^2/_3$; $^1/_3$; z) has an inversion point located in the same plane as the F^- ion. Therefore only 3 points are obtained:

- (1-y ; x-y ; z) : 1 ; 0 ; ¼
- (1+y-x ; 1-x ;z) : 1 ; 1 ; ¼
- and (x ;y ;z) : 0 ;0 ; ¼

Equivalent positions

The 2 equivalent positions of the F^- ions are (0 ;0 ; ¼) and (0 ; 0 ; ¾). These atoms are on an axis of the unit-cell because of the null coordinates x and y, so they are generated on the 3 other faces by translations. These new positions are : (1 ; 0 ; ¼), (1 ; 0 ; ¾), (0 ; 1 ; ¼), (0 ; 1 ; ¾), (1 ; 1 ; ¼) and (1 ; 1 ; ¾). (Fig. 8)

With the lattice translations, the crystal symmetries are not evident when only one unit-cell is observed. Only the observation of several adjacent unit-cells allows the visualisation of all the lattice symmetries (Fig. 9).

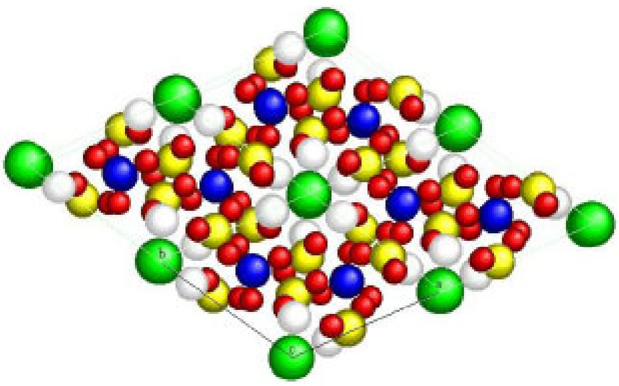


Figure 9: FAp crystal (2x2 cells - View [0001])

PO_4^{3-} ions are the only polyatomic ions of the FAp crystal. A phosphorus atom (valence: +5) is bonded to 4 oxygen atoms (valence: -2). If the PO_4^{3-} ion is totally isolated from crystal interactions, it can be drawn as a perfect tetrahedron, where the P atom is the gravity centre, and the O atoms the edges of the tetrahedron. In the ideal model, the P-O covalent bonds are 1.54 Å long (Radhakrishnan 1963, 1964) and the distance between two O atoms is 2.51 Å long. The O_i-P-O_j ($i \neq j$) angles are equal to 109°30'16". This molecule belongs to the cubic point group *Td* ($\bar{4}3m$). The P-O bonds are all equal, and there is no P=O bond, which is logical considering the valences of the P and O atoms. So a non-defined bond exists and is located on the 4 O Atoms and around the P atom.

To find the PO_4^{3-} ions in the FAp crystal, the atomic positions of P and O atoms have to be considered (Table 1). P, O_I and O_{II} atoms occur in the mirror-plane and form the basis of the PO_4^{3-} ion. The tetrahedron is completed by two O_{III} atoms out of the mirror planes and symmetrical by reflection. The covalent bonds still exists, but the tetrahedron is deformed according to the interactions between the PO_4^{3-} ion and its environment. The PO_4^{3-} ion is bonded to the local Ca^{2+} ions by way of its O atoms. These interactions distort the tetrahedron along the *c*-axis, the equality between the P-O bonds and between the O_i-P-O_j ($i \neq j$) angles is broken, except for the two atoms O_{IIIa} and O_{IIIb}, which remain equivalent. This means a decrease of the molecular symmetry, and the *Td* ($\bar{4}3m$) point group becomes the *Cs*(*m*) site group. The bonds and angles of the PO_4^{3-} ion are (Sudarsanan *et al.,* 1978) :

- P-O_I= 1.5337 Å, P-O_{II}= 1.5406 Å, P-O_{III}= 1.5342 Å,
- O_I···O_{II}= 2.538 Å, O_I···O_{III}= 2.529 Å, O_{II}···O_{III}= 2.487 Å, O_{IIIa}···O_{IIIb} = 2.473 Å,
- O_I-P-O_{II}= 111° 12', O_I-P-O_{III}= 111° 06' 36", O_{II}-P-O_{III} = 107° 57' 36" and O_{IIIa}-P-O_{IIIb}= 107° 19' 48".

However, the decrease of the symmetry and the P-O variations are not enough to destroy the non-defined bond, which favours the interaction between the PO_4^{3-} ion and its environment. Each PO_4^{3-} ion is bonded to a Ca_I^{2+} ion by its two O_{III} atoms and by O_I or O_{II}, and to an adjacent Ca_I^{2+} ion by the 4th O atom (O_{II} or O_I). In the same way, the PO_4^{3-} ion interacts with a Ca_{II}^{2+} ion by the 2 O_{III} atoms, and 2 adjacent Ca_{II}^{2+} ions by O_I or O_{II} (Fig. 10).

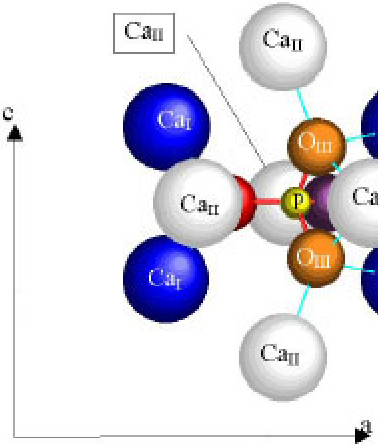


Figure 10: The PO_4^{3-} ion and its environment

The Ca_I^{2+} ions are spaced by *c*/2 and form columns along the $\bar{6}$ -axis at ($^1/_3$; $^2/_3$; z) and ($^2/_3$; $^1/_3$; z). Each Ca_I^{2+} ion is bonded to the Ca_I^{2+} ions above and below it by 3 O atoms from the mirror plane: 3 O_I above it, and 3 O_{II} below it. The distance between Ca_I^{2+} and O_I is 2.399 Å long and between Ca_I^{2+} and O_{II} 2.457 Å long. The Ca_I^{2+} ion also interacts with 3 O_{III} atoms, which are about in the same plan as the Ca_I^{2+} ion (distance between Ca_I^{2+} and O_{III}: 2.807 Å). So the Ca_I^{2+} ions are bonded to 9 O atoms by ionic bonds, and in this way they interact with the PO_4^{3-} ions (see Fig. 11).

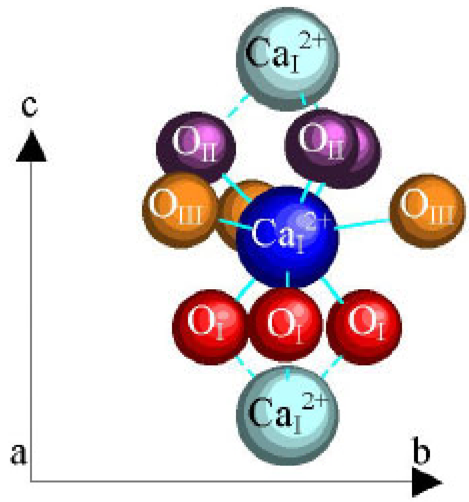


Figure 11: The Ca_I^{2+} ion and its environment

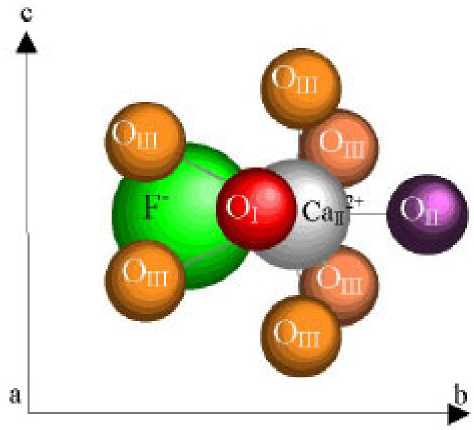


Figure 12: The Ca_{II}^{2+} ion and its environment

The Ca_{II}^{2+} ions are in the mirror-planes, and form triangles around the 6_3-axis. The Ca_{II}^{2+} ion is coordinated to a F^- ion, which is in the centre of the triangle (d(Ca_{II}^{2+} ; F) = 2.310 Å), and to 6 O atoms (one O_I, one O_{II} and 4 O_{III}) (Fig. 12). The distance between 2 Ca_{II}^{2+} ions is between 4.002 and 4.084 Å (Hughes *et al.,* 1989) according to the position of the 2 Ca_{II}^{2+} ions (in the same mirror-plane or not). The distance between Ca_{II}^{2+} ion and O atoms is equal to 2.701. 2.374 and 2.501 Å respectively for O_I, O_{II} and O_{III}. All the bonds are ionic except the Ca_{II}-F bond, which is partially covalent (Penel *et al.,* 1997).

Each F^- ion is bonded to the F^- ions above and below it (d (F ; F) = 3.44 Å) and to 3 Ca_{II}^{2+} ions (d (F ; Ca_{II}) = 2.463 Å) which form a triangle around it in the same mirror-plane (Hughes *et al.,* 1989, 1990). These F-Ca_{II} bonds are partially covalent (Penel *et al.,* 1997) (Fig. 13).

The crystalline structure (Fig. 14) is a succession of columns parallel to the *c*-axis, at the centre of the triangles perpendicular to the *c*-axis: the F^- ions are in the centre of Ca_{II}^{2+} triangles and the Ca_I^{2+} ions are in the centre of PO_4^{3-} triangles. This structure and the presence of numerous ionic bonds make FAp a very suitable host for many of substituents or dopants.

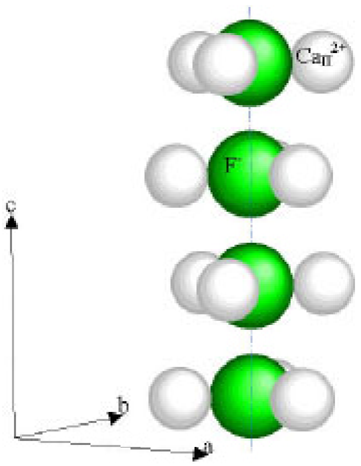


Figure 13 : Column of F^- ions

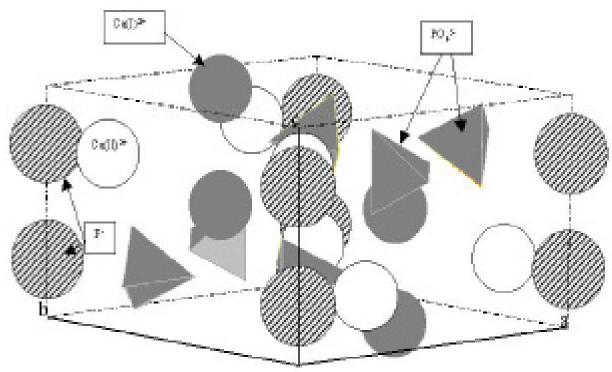


Figure 14: FAp unit cell viewed along the [0001] direction

Substitutions

Many types of substitution have been described, according the preferred substitution site. The main one, called Type-A substitution, is the substitution of the F^- ion by another ion X^- (X = Cl, OH, CO_3…) (Elliott, 1994; 1998; Hughes *et al.,* 1989; 1990; 1991; Kay *et al.,* 1964; Mackie and Young, 1974; O'Shea *et al.,* 1974; Penel *et al.,* 1997; Sudarsanan and Young, 1978). The second one is the PO_4^{3-} substitution (Penel *et al.,* 1997; Perdikatsis, 1991), called Type-B substitution. Some ions can substitute for the Ca^{2+} ions: Pb^{2+}, Nd^{2+}, Na^+ (Elliot, 1994; Mackie and Young, 1973; Miyake *et al.,* 1986). Finally, some dopants do not substitute at any particular site, but occur in a special position, which modifies the crystalline environment, e.g., Sb^{2+} or Mn^{2+} (DeBoer *et al.,* 1991; Hughes *et al.,* 1991; Suitch *et al.,* 1985). All the substitutions exist in nature, and most of them are reproducible in the laboratory.

The Type-A Substitution

This consists of replacing F^- ions by other X^- ions (X= OH, Cl, Br) or Y^{2-} (Y=O, CO_3). Replacement of F^- by a neutral molecule is also possible (H_2O, O_2, Ar, CO_2) (Elliot 1994; Trombe, 1973). This implies a weak increase of the *a*-parameter. However, a neutral molecule substitution, e.g., by H_2O or O_2, only exists in a few particular conditions, e.g., the hydration of enamel.

The most usual substitution is **substitution of the F^- ion by another monovalent ion**, e.g., OH^- or Cl^- ions. The X^- substituent is not exactly in the centre of the Ca_{II} atoms triangle, at z= ¼ or z=¾, but undergoes a displacement off these positions in the anionic column. This displacement varies according to the type of substituent: in hydroxyapatite (OHAp), the oxygen atom of the hydroxyl group is below or above the Ca_{II}^{2+} triangles at 0.3 Å of the F^- position (0; 0; 0.196), which causes a local disturbance (Hughes *et al.,* 1989; Kay *et al.,* 1964; Sudarsanan and Young, 1978). When the composition is close to a stoichiometric OHAp, the hydroxyl ions are always in these positions, and the space group becomes $P2_1/b$ (Elliot 1994; Hughes *et al.,* 1989) , with a pseudo-hexagonal structure ($b = 2a$, $g = 120°$) (Fig. 15).

In the same way, in a stoichiometric chlorapatite (ClAp), the Cl^- ions are in (0; 0; 0.444). A vacancy is created on the *c*-axis and the space group becomes $P2_1/b$ (Sudarsanan and Young, 1978). In the series between the two (ClAp and FAp) stoichiometric apatites, the displacement of X^- ions implies that of F^- ions according to their substitution rate, and causes a local disturbance, with a possible transformation from the hexagonal structure (space group $P6_3/m$) to a monoclinic one (space group $P2_1/b$) (Hughes *et al.,* 1989; 1990; Mackie and Young, 1974; Penel *et al.,* 1997; Sudarsanan and Young, 1978). The presence of F-X interactions first stabilises the hexagonal structure, then causes the transformation to a monoclinic structure (Hughes *et al.,* 1989; 1990). On the other hand, the unit-cell parameters are weakly modified: we note an increase of the *a*-parameter, and a decrease of the *c*-parameter (Hughes *et al.,* 1989; 1990). The anionic site environment undergoes some disturbance depending on the substitution rate. No PO_4^{3-} or Ca^{2+} ions are lost, but a change of their crystallographic positions is observed, in order to conserve the Ca-X bonds and to compensate the disorder due to the substitution. Then, we can observe a variation of about 0.2 percent of some crystallographic positions of PO_4^{3-} and Ca^{2+} ions when the quantity of F^- ions in the unit-cell decreases from 94 to 75% (Mackie and Young, 1973; Sudarsanan and Young, 1978).

In **a Y^{2-} ion substitution** (Y=O, CO_3), the two F^- ions of the unit-cell are substituted by one or more Y^{2-} ions (Elliott, 1998). This substitution can cause electrical charge

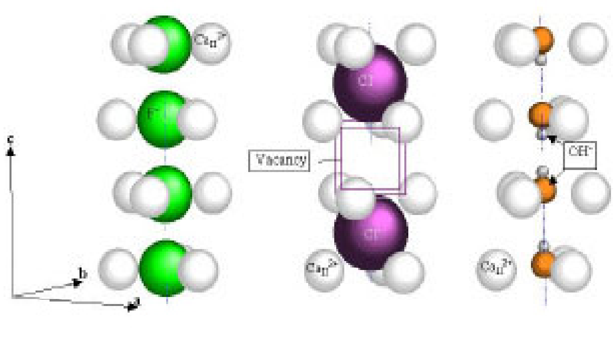


Figure 15: Apatite, F^-, OH^- and Cl^- columns

balance disorders, compensated by the existence of vacancies at F^- ion sites or in some cases by a loss of the screw-axis 6_3. Those F^- vacancies could appear in order to compensate for a loss of one or several Ca^{2+} ions too.

The Ca^{2+} substitution is often present in industrial applications, where rare-earth-doped FAp (e.g., Mn^{2+}, Nd^{3+}, or Sr^{2+}) (Fleet and Pan, 1997; Hughes *et al.,* 1991; Mackie and Young, 1973; Suitch *et al.,* 1985) are used to build fluorescence lamps. We find 2 or 3 types of Ca^{2+} substitutions, depending on whether the substituted sites are the Ca_I^{2+} sites, the Ca_{II}^{2+} sites or both sites. Generally, if the substituent does not have a valence equal to +2, the 2 sites are disturbed (Elliott 1994). If the substituent is in M^{2+} form, the substitution depends on the relative size of the substituent and the Ca^{2+} ion. According to Kreidler, the substituent radius for the Ca^{2+} site can be between 0.95 and 1.35 Å (Kreidler and Hummel, 1970). The largest substituents prefer the Ca(II) site, and the FAp hexagonal structure suffers when small cations M^{2+} fill Ca_I^{2+} sites (Elliot, 1994; Kreidler and Hummel, 1970).

The Ca^{2+} substitution by monovalent ions (K^+, Na^+) takes often place on Ca_I sites (Elliott 1994), creating a vacancy in F^- sites, and sometimes in Ca_I^{2+} sites.

If **the substituent is divalent** (Sr^{2+}, Pb^{2+}, Mg^{2+}), the preferentially substituted site is the Ca_{II}^{2+} site (Hughes *et al.,* 1991; Miyake *et al.,* 1986). We observed no loss of PO_4^{3-} ions, and the substitution rate is generally weak. The presence of dopant causes a contraction of the *c*-axis, an increase of the *a*-axis parameter (Hughes *et al.,* 1991), and a weak displacement of the different atoms. The substitution rate is 1:1, and the crystalline structure does not seem to be particularly troubled by the possible electronic disorder. We only noted an extension of the Ca_{II}-O distances, when they still existed (Hughes *et al.* 1991).

In the same way, when the two sites are substituted, the crystal sustained no major structural change (for example, substitution by Pb^{2+} (Miyake *et al.,* 1986) or by Cd^{2+} (Nounah and Lacout, 1992)). We just noted a increase of the unit-cell parameters and of M-O distances (M = Ca, Cd or Pb). On the other hand, a Ca_I^{2+} substitution had many consequences for the crystalline structure (Hughes *et al.,* 1991; Suitch *et al.,* 1985). A weak Mn^{2+} rate (occupation rate inferior to 0.42) does not cause large crystalline changes, because the Mn^{2+} ion is smaller than the Ca^{2+} ion and fits better into the $Ca(I)^{2+}$ surroundings rather than the Ca_{II}^{2+} surroundings. We only observed a reduction of Ca_I-O distances (Hughes *et al.,* 1991; Suitch *et al.,* 1985). However, a substitution rate higher than or equal to 48% had more extensive consequences. A Ca_I^{2+} substitution by a Mn^{2+} ion excluded any other Mn^{2+} ion from the cell in the Ca_I^{2+} site, excluded them in the Ca_{II}^{2+} site and caused the appearance of a vacancy in F^- sites (Elliott, 1994). Part of the O_{III} atoms were rejected from their positions, and the plane-mirrors disappeared. The crystal symmetry was broken, and the space group became $P6_3$ (Suitch *et al.,* 1985).

A Ca^{2+} substitution by a trivalent substituant (Sb^{3+}, Nd^{3+}) is relatively seldom seen. However, this type of substitution is used in the fabrication of fluorescent lamps. If the substituent rate is very weak (<2%), the Ca_{II}^{2+} sites are preferentially substituted, and we note no loss of PO_4^{3-}. The crystal seems to accept the electronic disorder (DeBoer *et al.,* 1991). The presence of dopant causes a reduction of the *c*-axis parameter, and an extension of the *a*-axis (Mackie and Young, 1973). The substitution ratio is 1:1, and the crystalline structure seems not affected by the eventual electronic disorder. However, when the substitution rate is higher, Ca^{2+} substitution by trivalent ions is accompanied by F^- substitutions by divalent ions and/or Ca^{2+} substitutions by monovalent ions (Elliot, 1994). In the particular case of Sb^{3+} substitution, the Sb^{3+} size is more important than the Ca^{2+} size. When the substitution rate is over 3%, the Sb^{3+} ions do not find a place in the Ca_{II}^{2+} sites but in ($^1/_3$; $^2/_3$; ¼) and ($^2/_3$; $^1/_3$; ¼), between the Ca_I^{2+} ions, on the $3(C_3)$ axis. A displacement of the Ca_I^{2+} ions and a rotation, or a loss, of PO_4^{3-} ions in order to compensate the imbalance were observed. The substitution rate is 2 Sb^{3+} for 3 adjacent Ca_I^{2+} (DeBoer *et al.,* 1991; Elliott, 1994).

The substitution of the PO_4^{3-} ions by a substituent such as XO_4^{3-} (X= V, As, Mn, Cr...) or CO_3^{2-} (Elliott, 1994; Kreidler and Hummel, 1970; Perdikatsis, 1991) is called **Type-B substitution**. When the substituent is of the type MO_4^{3-}, the substitution is partial or complete, with a substitution rate equal to 1:1. The *a*-axis and the *c*-axis parameters weakly increase, and we note a decrease of the *c/a* rate. According to Kreidler, the radii of the atom M must be between 0.29 and 0.6 Å to conserve the $P6_3/m$ structure (Kreidler and Hummel, 1970). However, a PO_4^{3-} substitution often implies some distortions of the crystal structure, or a loss of the hexagonal symmetry. It is called pseudo-hexagonal structure because the main observed distortion is that of the F^- ions (Kreidler and Hummel, 1970; Perdikatsis, 1991).

The substitution of PO_4^{3-} ions by CO_3^{2-} ones is generally accompanied by the loss of one F^- ion and one or several Ca_{II}^{2+} ions, in order to compensate for the electronic disorder due to the substitution. The carbonated apatite structure is still uncertain. Some scientists, such as Perdikatsis (1991) think, according to their study on carbonated FAp minerals, that the space group is still $P6_3/m$. However, it is difficult to prove this theory, and the substitution could imply a loss of symmetry, and then a change of the space group. Even the substitution way is uncertain: CO_3^{2-} was first seen occupying a PO_4^{3-} site, with an F^- ion or an OH^- one occupying the site of the 4th O. This theory was discarded, because it was thought that CO_3^{2-} cannot occupy a site on the screw axis *6*, because of its steric space. Later, because of the P-O bonds, another study proposed that the CO_3^{2-} ions are inclined on the *c*-axis, and occupy one of the tetrahedral PO_4^{3-} ion faces. Other substitution types were proposed, for example the substitution of 3 PO_4^{3-} ions by 4 CO_3^{2-} (Elliott, 1994), but this substitution has not yet been fully proven.

Conclusion

Because of the presence of several ions in its formula, FAp is a very suitable host for various substituents. Moreover, FAp finds many applications in various areas and its biological properties are not the least important ones. This explains the large interest for this compound. The presence of FAp in human enamel, its use in treatments against dental caries or osteoporosis, and its dangerous (or lethal) effects when high doses are given, justify the interest in FAp. Several substitutions are possible, and their effects can have both good or bad consequences for the organism, and could even be lethal. The FAp structure seems to accept most substituents, despite size or valence differences. Only the Ca^{2+} substitution often implies some modifications of the crystal structure, when the substituent is smaller than Ca^{2+} ion. These modifications do not affect only the Ca^{2+} sites but also the other sites of the unit-cell. However, many questions remain, because not all the substitution forms are well-known, e.g., the PO_4^{3-} substitution. In the present study, we have carried out a graphical construction of all the atoms of the FAp unit-cell using the symmetry operators of the $P6_3/m$ space group. The knowledge of such symmetries is not only useful for understanding the very structure of FAp but also for the detection of structural modifications induced by substitutions and hence for the understanding the behaviour of biological and synthetic calcium phosphate phases. We believe that such a description is useful to the biomaterials community.

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Discussion with Reviewers

D.B. Jones: "HA in the body slowly 'matures' by hydration. How is hydration affected by F in the molecule?
Authors: In HA, the oxygen atom of the hydroxyl group is below or above the Ca_{II}^{2+} triangles at 0.3 Å of the F^- position (0; 0; 0.196) which causes a local disturbance [Hughes *et al.* 1989, Kay *et al.* 1964, Sudarsanan and Young 1978] with a possible transformation from the hexagonal structure (space group $P6_3/m$) to a monoclinic one (space group $P2_1/b$). For steric reasons, this leaves room for indirect H_2O substitution at the column. These disturbances can favour the hydratation of the apatite structure. In FAp, the fluoride ion is located at z = ¼, in the centre of the Ca_{II}^{2+} triangles, where it forms partially covalent Ca_{II}-F interactions. It is hence more difficult for a F^- ion to be displaced in order to leave room for a H_2O molecule.

D.B. Jones: Does F also form other compounds in bone than reacting with HA?
Authors: We cannot answer this question, and have no knowledge of other compounds formed in bone with fluoride, except for F,OH-Ap or F,CO_3-Ap.

S. Downes: Would the authors clearly indicate why the information generated using this technique could have value in the field of Biomaterials?
Authors: Both mineral phases of calcified tissues and synthetic calcium phosphate materials have a structure similar to that of FAp. Moreover, the physical and chemical properties of these apatites are related to their structure. This technique allows a better visualisation of the FAp structure and so favours a better understanding of the substitution mechanisms and of the physical and chemical properties of the apatites.

S. Downes: Would the authors like to strengthen their introduction by also indicating how HA can be substituted with groups such as carbonates? Can this technique be used to model these HA s?
Authors: This technique needs some precise data about the structure of the molecule we want to model. Except for a few cases, the structure of the carbonated apatites is not completely known. Therefore the representation of these apatites by this technique can, for the moment, only be a working hypothesis.