A SURVEY OF FELDSPAR TWINNING

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Introductionary remarks

A common feature of the feldspars, triclinic as well as monoclinic, is the frequent occurrence of twinning, more than twenty different laws having been described. As is well known to petrologists, the twinning of plagioclases plays an important rôle in the determination of the anorthite content by microscopic methods. But besides this practical aspect, the twinning of the feldspars also offers interesting problems from a purely crystallographical point of view. It is therefore believed that a general survey of the hitherto described twinning laws may well be presented in this place.

Generalities on twinning

Twinning laws can be described either by stating the twin-axis or the twin-plane which is by definition normal to the former. In what follows, definitions according to twin-axes are preferred. The plane along which the two twinned individuals are in contact is called the composition plane. It can be identical with the twinplane but is not necessarily so.

As already recognized by Kayser in 1835 and by Tschermak in 1880, three types of twinning-laws can be distinguished:

1) Normal twins: The twin-axis is normal to a possible crystal face
2) Parallel twins: The twin-axis is parallel to a possible crystal edge
3) Complex twins: The twin-axis is normal to a possible crystal edge and is at the same time parallel to a possible crystal face.

As an example of a normal twin the Albite law may be quoted: twin-axis (TA) normal to (010). The well-known Carlsbad law with $TA = [001]$ represents the parallel twins and as an example for a complex twin we may quote the Roc Tourné law with TA normal to [001] and parallel to (010), this being generally written as

$$TA = \frac{\perp [001]}{(010)}.$$

The twinning of the feldspars

Making use of Tschermak's definition and at the same time adopting the concept of hemitropy (meaning half-a-turn) as first proposed by Hauy, the twin-laws of the feldspars hitherto discovered can be listed as follows:

A. Normal hemitropies

	Twin-law	twin-axis	Author and remarks
a)	Albite	$\perp (010)$	Rose (1823).
b)	Manebach (Four-la-Brouque)	$\perp (001)$	On orthoclase already known to Romé de l'Isle in 1783. Designation "Manebach" by Blum (1863), "Four-la-Brouque" by Gonnard (1883). First observed on triclinic feldspars by Kayser (1835).
c_1)	Baveno-*r*	$\perp (021)$	On orthoclase already known to Romé de l'Isle in 1783 and Hauy in 1801.
c_2)	Baveno-*l*	$\perp (0\bar{2}1)$	Designation "Baveno" already in use before 1830 as applied in this year also to albite by Weiss and Neumann (Neumann, 1830).
d_1)	No special name yet given	$\perp (111)$	Discovered on orthoclase by Drugman (1938) and by Köhler (1950)
d_2)		$\perp (1\bar{1}1)$	on plagioclase.
e_1)	No special name yet given	$\perp (130)$	On orthoclase already known to Naumann (according to Hintze), also observed on plagioclase by Belowsky (1892).
e_2)		$\perp (1\bar{3}0)$	On plagioclase observed by Köhler (1950).

The following normal hemitropies are only known with certainty to occur on orthoclase. On plagioclase they are either doubtful or not yet found. For plagioclase some of them would resolve into two distinct laws to be designated as "right" (*-r*) and "left" (*-l*) as already done for the Baveno law.

f)	Prism (110)	$\perp$ (110)	Observed by Laspeyres (1877) and by Haushofer (1879). For triclinic feldspars the designation "Prism" law would not be correct.
g)	*X*-law	$\perp$ (100)	Theoretically predicted by Kayser (1835). On orthoclase observed by Laspeyres (1877), perhaps also by Herrmann (1924) on plagioclase.
h)	Cunnersdorf (designation proposed by present author)	$\perp$ $(\bar{2}01)$	Observed on orthoclase by Klockmann (1882)
i)	Breithaupt law (designation proposed by present author)	$\perp$ $(\bar{1}11)$	On orthoclase already known to Breithaupt 1858 as stated by Hintze (1897)
k)	Goodsprings	$\perp$ $(\bar{1}12)$	Observed on orthoclase by Drugman (1938).

B. Parallel hemitropies

	twin-law	twin-axis	author and remarks
l)	Pericline	[010]	Breithaupt (1823), Kayser (1835) and especially Vom Rath (1876).
m)	Ala (Estérel)	[100]	Kayser (1835). Designation "Ala" by Des Cloizeaux (1862), "Estérel" by Lacroix (1897).
n)	Carlsbad	[001]	Already known to Hauy on orthoclase in 1801. Designation probably first given by Quenstedt (?) (1855). For plagioclase first observed by Kayser (1835).

Hitherto only known for orthoclase are the following laws which like the Baveno law would also resolve into two distinct ones for triclinic feldspars:

o)	Petschau	[1$\bar{1}$0]	Tschermak (1887), also observed by Goldschmidt and Wright (1897) and Drugman (1927).
p)	Nevada	[$\bar{1}$12]	Drugman (1938).

C. Complex hemitropies

	twin-law	twin-axis	author and remarks
q)	Manebach-Ala = Acline	$\frac{\perp [100]}{(001)}$	Already observed by Kayser (1835). In later times generally believed to be a special case of the Pericline law with invariable composition plane (001). Rediscovered by Duparc and Reinhard (1923) and Gysin (1923).
r)	Albite-Ala (Albite-Estérel)	$\frac{\perp [100]}{(010)}$	Kayser (1835).
s)	Manebach-Pericline = Scopi	$\frac{\perp [010]}{(001)}$	Kayser (1835). Rediscovered by Viola (1900) on albite from Piz Scopi, Grisons, Switzerland, and named thereafter.
t)	Albite-Carlsbad = Roc Tourné	$\frac{\perp [001]}{(010)}$	Kayser (1835), also described by Rose (1865). Designation by Lacroix (1897).
u)	*X*-Carlsbad = Acline-*B*	$\frac{\perp [001]}{(100)}$	Predicted by Kayser (1835) on theoretical grounds. Position of twin-axis nearly identical with that of Acline law and not to be distinguished from it by *U*-stage methods. The very rare so-called Acline-*B* twins of Duparc and Reinhard (1923) with composition plane (100) are therefore believed by recent authors to be *X*-Carlsbad complex twins. Also observed by Barth (1928) on triclinic adularia.

v) *X*-Pericline = Carlsbad-*B*	$\frac{\perp [010]}{(100)}$	Predicted by Kayser (1835) on theoretical grounds. Position of twin-axis nearly identical with that of Carlsbad law and not to be distinguished from it by *U*-stage methods. The very rare so-called Carlsbad-*B* twins of Duparc and Reinhard (1923) with composition plane (100) are therefore supposed by recent authors to be *X*-Pericline complex twins.

All of the twin-axes listed above are plotted for a triclinic feldspar (anorthite) in stereographic projection in Fig. 1, the laws hitherto observed on monoclinic feldspar only having been resolved in two distinct ones, "right" and "left". The figure shows clearly that some of the twin-axes differ but very little in their position. It will, therefore, not always be possible to distinguish them from each other, at least by *U*-stage methods. In some cases consideration of the composition plane will help in deciding which twin-law is present. It seems also if there were no clear relationship between the location of the twin-axes and the morphology. With this respect a much clearer picture is obtained if the notable pseudo-symmetry of the feldspars is taken into account as first suggested by v. Fedorow (1897, 1902) who was later followed by Beckenkamp (1919) and Niggli (1926).

Pseudosymmetry of the feldspars

As is well known, the feldspars are either monoclinic or triclinic, the latter being strongly pseudo-monoclinic as the angles α and γ do not differ very much from right angles. In addition the feldspar group taken as a whole is also highly-pseudo-cubic as was first recognized by v. Fedorow (1902). The *c*-axis of the conventional setting shows well expressed pseudo-hexagonal features and the *a*-axis pseudo-tetragonal character. A transformation by which the *c*-axis of the old system becomes [111] in the new one, wheras *a* is changed into *c* and *b* into $[1\bar{1}0]$, results in a new setting showing the pseudo-cubic symmetry very clearly (Figure 2).

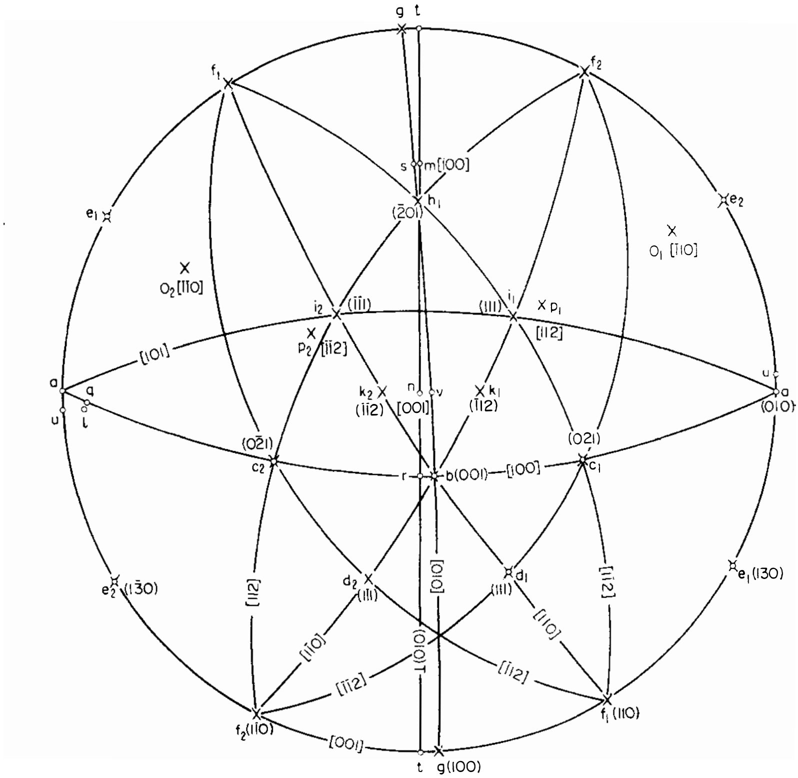

Figure 1. Stereographic projection of the twin axes hitherto known for feldspar in conventional setting. Open circles: twin-axes known to occur on triclinic feldspars, crosses: twin-axes known to occur on monoclinic feldspars.

Twin-laws: *a* Albite, *b* Manebech, c_1 Baveno-*r*, c_2 Baveno-*l*, d_1 (111), d_2 $(1\bar{1}1)$, e_1 (130), e_2 $(1\bar{3}0)$, *f* (100), *g* *X*-law, *h* Cunnersdorf, *i* Breithaupt, *k* Goodsprings, *l* Pericline, *m* Ala, *n* Carlsbad, *o* Petschau, *p* Nevada, *q* Manebach-Ala = Acline, *r* Albite-Ala, *s* Manebach-Pericline = Scopi, *t* Albite-Carlsbad = Roc Tourné, *u* *X*-Carlsbad = Acline-*B*, *v* *X*-Pericline = Carlsbad-*B*.

The indices $[uvw]^*$ of the co-ordinate axes of the new system, here called a_1, a_2, a_3 can be expressed in terms of those of the old ones $[uvw]$, called *a*, *b*, *c*, and vice versa by the following relations:

$$
\begin{aligned}
a_1 &= [100]^* = [1\bar{1}2] \qquad & a &= [100] = [00\bar{2}]^* \\
a_2 &= [010]^* = [112] \qquad & b &= [010] = [\bar{2}20]^* \\
a_3 &= [001]^* = [\bar{2}00] \qquad & c &= [001] = [111]^*
\end{aligned}
$$

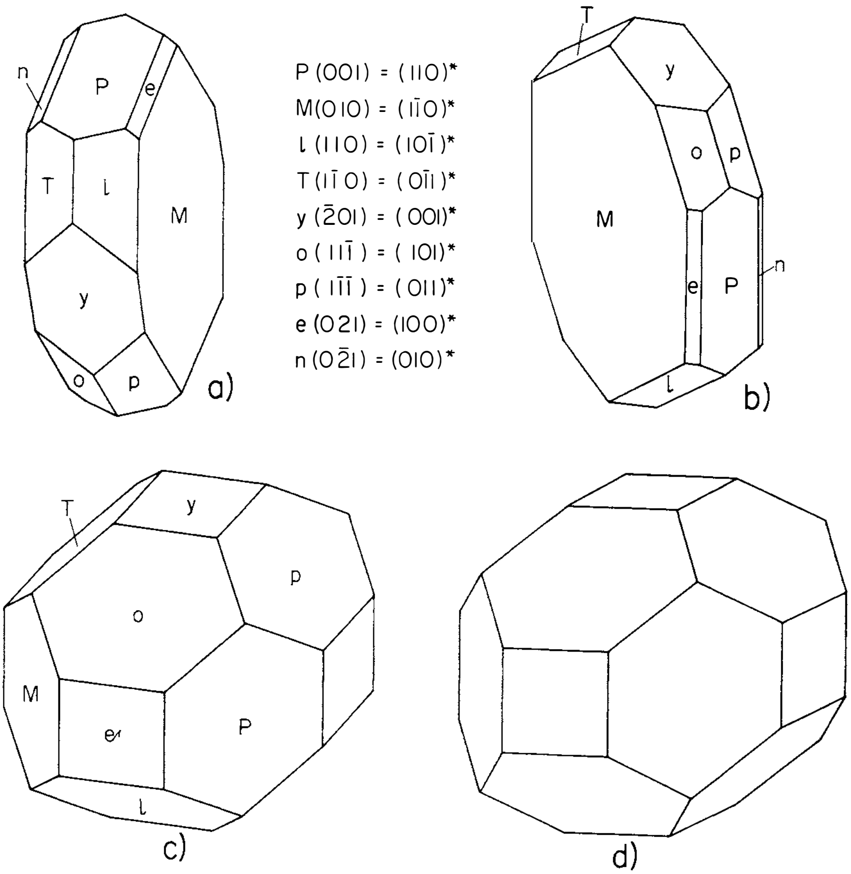

Figure 2. Pseudo-cubic symmetry of feldspars exemplified on anorthite.

a) Anorthite crystal, conventional setting.

b) Same crystal in pseudocubic setting.

c) Same crystal again, drawn with equal central distances for pseudo-cubically corresponding faces, the pseudo-hexahedron and pseudo-rhombic dodecahedron standing clearly out.

d) Cubic crystal with (100) and (110), for comparison.

The inter-relation of the indices (hkl) for the faces in the old and $(hkl)^*$ in the new system reads as follows:

$$h^* = h - k + 2l \qquad h = -2l^*$$
$$k^* = h + k + 2l \qquad k = -2h^* + 2k^*$$
$$l^* = -2h \qquad l = h^* + k^* + l^*$$

and those for the zones $[uvw]$ in the old and $[uvw]^*$ in the new system:

$$\left.\begin{aligned} u^* &= w - 2v \\ v^* &= w + 2v \\ w^* &= w - 2u \end{aligned}\right\} \qquad \left.\begin{aligned} u &= u^* + v^* - 2w^* \\ v &= -u^* + v^* \\ w &= 2u^* + 2v^* \end{aligned}\right\}$$

From the conventional axial ratios for

Orthoclase	$a:b:c = 0.6585:1:0.5554$	$\beta = 116°3'$ (v. Kokscharow)
Albite An_4	$a:b:c = 0.6352:1:0.5548$	$\alpha = 94°15'$, $\beta = 116°36'$, $\gamma = 87°46'$ (Krebs, 1921)
Anorthite An_{97}	$a:b:c = 0.6352:1:0.5505$	$\alpha = 93°10'$, $\beta = 115°53'$, $\gamma = 91°16'$ (Kratzert, 1921)

the following ones for the new setting can be calculated (Burri, 1934):

Orthoclase	$a_1:a_2:a_3 = 1:1:0.9255$	$\alpha_1 = 96°53'$, $\alpha_2 = 96°53'$, $\alpha_3 = 89°17'$
Albite An_4	$a_1:a_2:a_3 = 1.0629:1:0.9218$,	$\alpha_1 = 93°15'$, $\alpha_2 = 93°46'$, $\alpha_3 = 89°33'$
Anorthite An_{97}	$a_1:a_2:a_3 = 1.0776:1:0.9326$,	$\alpha_1 = 95°35'$, $\alpha_2 = 96°52'$, $\alpha_3 = 89°51'$

They show very clearly the highly pseudo-cubic symmetry with only slight deviation from true cubic symmetry.

Although the new setting seems very suggestive at first sight, it has not been generally adopted by subsequent authors. The main reason is probably that the symmetry plane of the monoclinic feldspars becomes $(\bar{1}10)^*$ in the new setting and the digonal symmetry axis becomes $[\bar{1}10]^*$. This is not in accordance with the rules universally followed for the setting of monoclinic crystals.

A close inspecting of the more common faces of the feldspars clearly shows that in the new setting they correspond to simple pseudo-cubic forms, e.g. the pseudo-rhombic dodecahedron $\{110\}^*$, pseudo-hexahedron $\{100\}^*$ and pseudo-icositetrahedron $\{211\}^*$ as shown by the following tabulation:

$$\left.\begin{aligned} (001) &= (110)^* & (\bar{1}\bar{1}1) &= (101)^* \\ (0\bar{1}0) &= (1\bar{1}0)^* & (\bar{1}10) &= (\bar{1}01)^* \\ (\bar{1}11) &= (011)^* & (\bar{1}\bar{1}0) &= (0\bar{1}1)^* \end{aligned}\right\} \text{Pseudo-rhombic dodecahedron } \{110\}^*$$

All feldspars show excellent cleavage after $(001) = (110)^*$ and

$(010)=(\bar{1}10)^*$. As additional cleavage directions mention is occasionally made of $(110)=(01\bar{1})^*$, $(1\bar{1}0)=(10\bar{1})^*$, $(\bar{1}\bar{1}1)=(101)^*$ and $(1\bar{1}\bar{1})=(0\bar{1}\bar{1})^*$. As all six faces of the pseudo-rhombic dodecahedron are thus represented, the cleavage of the feldspars can be described as pseudo-rhombic dodecahedral.

$$\left.\begin{array}{l}(021)=(100)^*\\(0\bar{2}1)=(010)^*\\(\bar{2}01)=(001)^*\end{array}\right\}\ \text{Pseudo-hexahedron}\ \{100\}^*$$

$$\left.\begin{array}{llll}(\bar{1}\bar{1}2)=(211)^* & (\bar{1}\bar{3}1)=(2\bar{1}1)^* & (\bar{1}30)=(\bar{2}11)^* & (\bar{1}1\bar{1})=(\bar{2}\bar{1}1)^*\\(\bar{1}12)=(121)^* & (\bar{1}\bar{3}0)=(1\bar{2}1)^* & (\bar{1}31)=(\bar{1}\bar{2}1)^* & (\bar{1}\bar{1}\bar{1})=(\bar{1}\bar{2}1)^*\\(\bar{1}01)=(112)^* & (\bar{2}\bar{2}1)=(1\bar{1}2)^* & (\bar{2}21)=(\bar{1}12)^* & (\bar{1}00)=(\bar{1}\bar{1}2)^*\end{array}\right\}\ \begin{array}{l}\text{Pseudo-}\\\text{icosite-}\\\text{trahedron}\\\{211\}^*\end{array}$$

As for the twin axes of the twin laws enumerated above, the transformation shows that in the new system they correspond without exception, either to normals or pseudo-normals of faces with indices not more complicated than those of the pseudo-icositetrahedron $\{211\}^*$ or to edges with the same simple indices or to directions close to them. Thus we are able to reduce all of the hitherto observed feldspar twin laws to a system of striking simplicity as tabulated herewith:

Systematic survey of the hitherto formulated feldspar twin laws with regard to the pseudo-cubic symmetry of the feldspars

I. Pseudo-hexahedral twin laws

a) Normal hemitropies

	twin law	twin axis (conventional setting)	twin axis (pseudo-cubic setting)	
1 a)	Baveno-*r*	$\perp$ (021)	$\perp$ (010)*	
1 b)	Baveno-*l*	$\perp$ $(0\bar{2}1)$	$\perp$ (100)*	
2)	Cunnersdorf	$\perp$ $(\bar{2}01)$	$\perp$ (001)*	

b) Parallel hemitropies

3)	Ala (Estérel)	[100]	[001]*	

c) Complex hemitropies

4)	Manebach-Pericline (Scopi)	$\dfrac{\perp [010]}{(001)}$	$\dfrac{\perp [\bar{1}10]^*}{(110)^*}$,	close to [001]*

II. Pseudo-octahedral twin laws (pseudo-spinel laws)

a) Normal hemitropies

not known

b) Parallel hemitropies

5)	Carlsbad	[001]	[111]*
6a)	Petschau-*r*	[110]	$[1\bar{1}1]$*
6b)	Petschau-*l*	$[1\bar{1}0]$	$[\bar{1}11]$*

c) Complex hemitropies

7) *X*-Pericline (=Carlsbad-*B*) $\frac{\perp [010]}{(100)}$ $\frac{\perp [\bar{1}10]^*}{(11\bar{2})^*}$, close to [111]*

III. Pseudo-rhombic dodecahedral twin laws

a) Normal hemitropies

8)	Albite	$\perp$ (010)	$\perp$ $(\bar{1}10)$*
9)	Manebach	$\perp$ (001)	$\perp$ (110)*
10a)	"Prisme"-*r*	$\perp$ (110)	$\perp$ $(0\bar{1}1)$*
10b)	"Prisme"-*l*	$\perp$ $(1\bar{1}0)$	$\perp$ $(\bar{1}01)$*
11a)	Breithaupt-*r*	$\perp$ $(\bar{1}11)$	$\perp$ (011)*
11b)	Breithaupt-*l*	$\perp$ $(\bar{1}\bar{1}1)$	$\perp$ (101)*

b) Parallel hemitropies

12)	Pericline	[010]	$[\bar{1}10]$*
13a)	Nevada-*r*	$[\bar{1}12]$	[011]*
13b)	Nevada-*l*	$[\bar{1}\bar{1}2]$	[101]*

c) Complex hemitropies

14) Manebach-Ala = Acline $\frac{\perp [100]}{(001)}$ $\frac{\perp [001]^*}{(110)^*}$, close to $[\bar{1}10]$*

15) Albite-Ala $\frac{\perp [100]}{(010)}$ $\frac{\perp [001]^*}{(\bar{1}10)^*}$, close to [110]*

16) *X*-Carlsbad (=Acline-*B*) $\frac{\perp [001]}{(100)}$ $\frac{\perp [111]^*}{(\bar{1}\bar{1}2)}$, close to $[\bar{1}10]$*

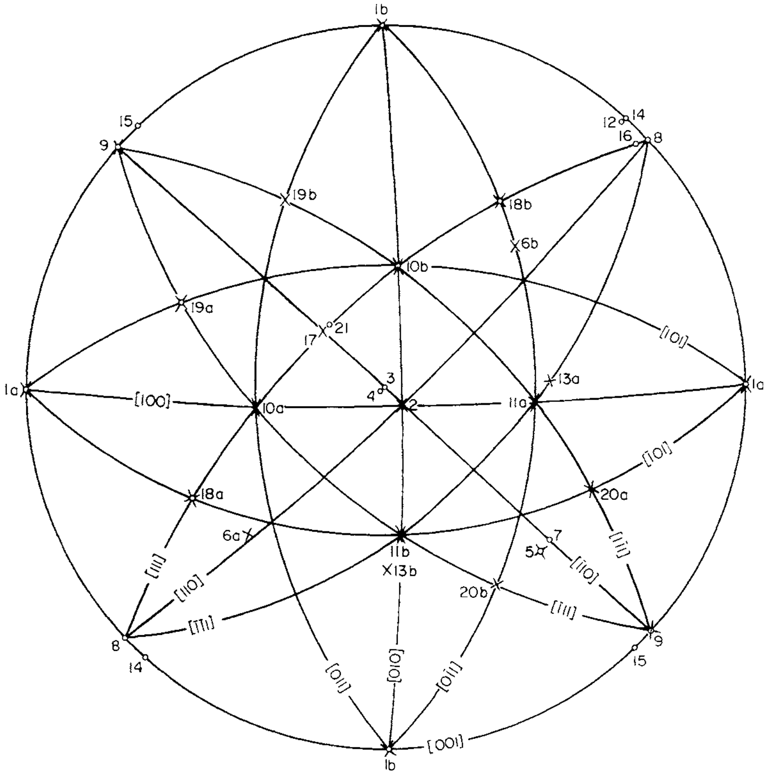

Figure 3. Stereographic projection of the hitherto known twin-axes in pseudo-cubic setting. Open circles: twin-axes known to occur on triclinic feldspars, crosses: twin-axes known to occur on monoclinic feldspars.

Pseudo-hexahedral twin-laws: 1a Baveno-*r*, 1b Baveno-*l*, 2 Cunnersdorf, 3 Ala, 4 Manebach-Pericline = Scopi.

Pseudo-octahedral twin-laws: 5 Carlsbad, 6a Petschau-*r*, 6b Petschau-*l*, 7 *X*-Pericline = Carlsbad-B,.

Pseudo-rhombic dodecahedral twin-laws: 8 Albite, 9 Manebach, 10a "Prisme"-*r*, 10b "Prisme"-*l*, 11a Breithaupt-*r*, 11b Breithaupt-*l*, 12 Pericline, 13a Nevada-*r*, 13b Nevada-*l*, 14 Manebach-Ala = Acline, 15 Albite-Ala, 16 *X*-Carlsbad = Acline-B.

Pseudo-icositetrahedral twin-laws: 17 *X*-law, 18a "Prisme" (130), 18b "Prisme" ($1\bar{3}0$), 19a (111), 19b ($1\bar{1}1$), 20a Goodsprings-*r*, 20b Goodsprings-*l*, 21 Roc Tourné.

IV. Pseudo-icositetrahedral twin laws

a) Normal hemitropies

17)	*X*-law	⊥ (100)	⊥ ($\bar{1}\bar{1}2$)*
18a)	"Prisme" (130)	⊥ (130)	⊥ ($1\bar{2}1$)*

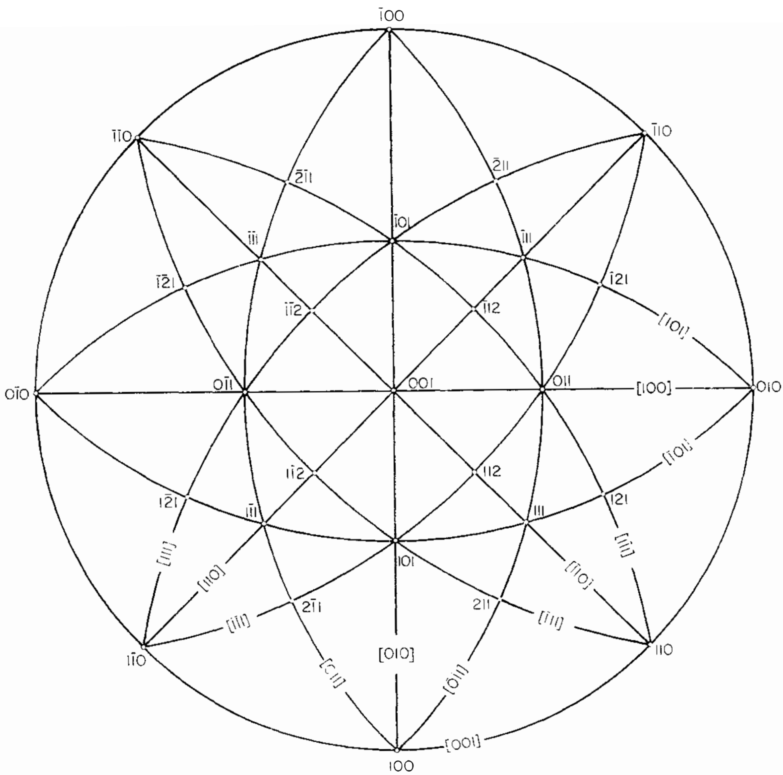

Figure 4. Stereographic projection of cubic crystal showing the forms (100) (111) (110) (211), for comparison with Figure 3.

18b)	"Prisme" $(1\bar{3}0)$	$\perp (1\bar{3}0)$	$\perp (\bar{2}11)^*$
19a)	--	$\perp (111)$	$\perp (\bar{1}\bar{2}1)^*$
19b)	–	$\perp (1\bar{1}1)$	$\perp (\bar{2}\bar{1}1)^*$
20a)	Goodsprings-*r*	$\perp (\bar{1}12)$	$\perp (121)^*$
20b)	Goodsprings-*l*	$\perp (\bar{1}\bar{1}2)$	$\perp (211)^*$

b) Parallel hemitropies

not known

c) Complex hemitropies

21) Roc Tourné (Albite-Carlsbad) $\dfrac{\perp [001]}{(010)}$ $\dfrac{\perp [111]^*}{(\bar{1}10)^*}$. close to $[11\bar{2}]^*$

The stereographic projection Figure 3 shows clearly the highly pseudo-cubic symmetry as well as the location of the twin axes in the positions mentioned. In contradistinction to Figure 1 the general principle governing the distribution of the twin axes stands out clearly as they can be recognized as normals or pseudonormals to faces of simple pseudo-cubic indices or simple edges. These clear relations also offer valuable suggestions for discovering or checking new and hitherto unknown twin laws. In Figure 4 the stereographic projection of a cubic crystal showing the forms {100}, {111}, {110} and {211} is given for comparison with Figure 3.

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