# Twinning in anorthoclase megacrysts from phonolitic eruptions, Erebus volcano, Antarctica

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# Title:

# Twinning in anorthoclase megacrysts from phonolitic eruptions, Erebus volcano, Antarctica

## Running title: Anorthoclase twins at Erebus volcano (Antartica)

**Plan of the article**


1 Introduction .... 2
2 State of the art: Feldspar habits and twins .... 4
2.1 Feldspar twins .... **Erreur ! Signet non défini.**
2.2 Single crystals habit of anorthoclase .... **Erreur ! Signet non défini.**
3 Materials and methods .... 6
3.1 Samples .... 6
3.2 Methods .... 7
4 Results .... 8
4.1 Single crystals habit of anorthoclase .... 8
4.2 Symmetrical, asymmetrical, Y shaped and X shaped Carlsbad B twins .... 8
4.3 The re-entrant corner effect .... 10
4.4 Baveno twins .... 12
4.5 Prism twin .... 12
4.6 Manebach twin .... 12
4.7 B or Cunnersdorf twin .... 13
4.8 Erebus twin: a newly described twin .... 14
4.9 Tazieff twin: another new twin. .... 14
4.10 Albite twin .... 15
4.11 Single and near single groups: rare or questionable to doubtful twins .... 15
5 Conclusion .... 17



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# Twinning in anorthoclase megacrysts from phonolitic eruptions, Erebus volcano, Antarctica

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**Abstract**

Anorthoclase is a **major** component of **in trachytic and phonolitic lavas**. Mount Erebus volcano is well known for its anorthoclase **megacrysts which show a range of twin morphologies**. **Thanks to a set of more than 400 specimens collected by volcanologist Haroun Tazieff, we have revisited and improved the knowledge about the twins from this locality, and documented the crystals' shapes, sizes and frequencies.** The status of the X Carlsbad B twin **is** revised. Several twins, not yet mentioned **from this locality, are identified**. Two new **types of** twins (referred **to** here as Erebus and Tazieff) **are described, extending our knowledge of twins**.

**Keywords**

**Twin crystal; anorthoclase; feldspar; Erebus; Carlsbad twin; Erebus twin; Tazieff twin**.

## 1. Introduction

Mount Erebus (3794 m) on Ross Island (Antarctica) is a continuously active volcano with a permanent phonolite lava lake. **Petrologically, Mount Erebus evolved over 1.3 million years from basanites to** anorthoclase-rich phonolite **now being erupted** (e.g. Kyle et al., 1992; Kelly et al., 2008, **Esser et al., 2004**).

The **younger phonolitic** geochemical history of the volcano has been thoroughly **documented and shows that the phonolitic composition has been stable for over the last**

**10,000 years (Caldwell and Kyle, 1994,** Kelly et al., 2008, **Sims et al. 2008, 2013, Iverson et al., 2014**).

**“Anorthoclase” is an intermediate member of the high albite-sanidine alkali feldspar solid solution. It has been discredited as a mineral species by IMA but this name remains widely used, especially by geologists and mineralogists studying Erebus. To avoid confusion, we will continue to use this term here.** Anorthoclase crystals are abundant **as lag gravel on the slopes of the crater, next to its summit**, and are renowned for their **large sizes**. They can reach **over** 10 cm in length, **much larger than anorthoclase crystals typically found in lavas. The crystals have eroded out of phonolitic bombs erupted on the upper slopes of Mount Erebus. Because of their large size, the anorthoclase are often** called megacrysts. The **crystals** are not perfect, their edges are more or less irregular, their surfaces somewhat rough, sometimes **they are partly covered by remaining lava glass, and occasionally they are more or less corroded and altered by gases from the volcanic plume emitted by the lava lake**.

Mount Erebus anorthoclases show remarkable oscillatory zoning (Kyle, 1977; Caldwell & Kyle, 1994; **Dunbar** et al., 1994; Kelly et al., 2008; Moussallam et al., 2015). Analyses **by** Kelly et al. (2008) **of 8 anorthoclase crystals in bombs erupted in 1985 show that the crystals have** a compositional range of $An_{10.3-22.9}Ab_{62.8-68.1}Or_{11.4-27.2}$. Moussallam et al. (2015) explained **the** oscillatory composition and zoning by **circulation of** the anorthoclase crystals **in** the plumbing system and over distances of up to several kilometers. They estimated that 1-cm wide anorthoclase crystals are at least 14 years old and **probably** record cycles **from a deeper magma chamber** up to the lava lake. The lattice parameters of the Erebus anorthoclase (triclinic) crystals measured by Carmichael and MacKenzie (1964), for a composition of $An_{4.4}Ab_{72}Or_{22.5}Cn_{0.4}Sl_{0.7}$ (Cn for celsian (Ba end-member) and Sr for slawsonite (Sr end-member)) are:

$a$ = 8.263 Å, $b$ = 12.935 Å, $c$ = 7.138 Å and $\alpha$ = 92°15’, $\beta$ = 116°19’, $\gamma$ = 90°10’ ($b$ being the parameter in the direction that corresponds to the binary axis in monoclinic feldspars, **the authors did not include error limits**). **Other physical properties are discussed by Boudette and Ford (1969). We refer to Mason et al. (1982) for trace element contents in Erebus anorthoclase**.

The specimens of this study were collected by the French volcanologist Haroun Tazieff in 1974. While anorthoclase crystals **have been** largely studied to understand the**ir** geochemical changes **at** Mount Erebus volcano, they are here examined to better constrain their twinning.

## 2. State of the art: Feldspar and twins

### 2.1 **Twin definitions**

**A twin is defined as an intergrowth (an edifice) of two (or more) homogeneous similar crystals (called individuals), in which the two adjacent individuals have different orientations, characterized by a geometrical operation called *twin operation*. The difference between an accidental intergrowth and a twin is based on several criteria. The first one postulated by Friedel (1904) is that the edifice suspected to be a twin must be more or less frequent, or that the suspected twin (crystallographic) operation is remarkable. Friedel also developed the so-called "*reticular theory*" which postulates there is a sublattice, called *twin lattice* shared by the two individuals. This sublattice has a lattice element (plane or axis) on which the twin operation occurs and a lattice element (axis or plan) (quasi)-perpendicular to it. These two elements define the cell of the sublattice. The ratio of the mesh volume of the twin lattice on the mesh volume of the unit cell of the individual is the *twin index*, n. It indicates the degree of lattice restoration between the twin individuals sharing a partially coherent interface (composition plane). When the two elements are not perpendicular (pseudo-symmetry) the deviation angle from perpendicularity, ω, is called *obliquity*. On the basis of his life work on twins, Friedel has established the empirical criteria: $n \leq 6$ and $\omega \leq 6$. Twins following these limits are now called *Friedelian twins* (e.g. Nespolo & Ferraris, 2005, 2006). To explain some *non Friedelian twins*, some authors (Nespolo & Ferraris, 2005, 2009; Pignatelli et al., 2011) have elaborated an extension of the reticular theory with the *hybrid twins* in which two or more twin sublattices exist. The overall lattice restoration is measured by the effective twin index, $n_E$, an extension of n. Since this index does not explain the frequency of some twins, the reticular theory has been improved by Marzouki et al. (20014a), by taking into account symmetries inside the crystal cell, i.e. the (pseudo-)eigensymmetry of crystallographic orbits. These authors (Marzouki et al., 2014b) have analyzed the eigensymmetries of the most common Saint–Andrew staurolite twin ($n_E = 6$ from $n = 12$) and found that the anion sublattice is restored by the twin law and that the cation restoration in the Saint-Andrew twin is better than in other staurolite twins.**

**Intergrowths (with contact planes) with very high n index are found in twins of twins, domains and crystalline interface structures (Bollman, 1970; Hahn et al., 2014). In these cases, the substructure is called the coincidence site lattice (CSL) and n becomes Σn. The boundary between twin plane (composition) and crystalline interface is not always obvious.**

The feldspar family is well known for its high number of twins **(Hintze, 1897, Barth, 1969, Smith, 1974, Deer et al., 2013)**. These twins are well described within the rotation-contact twin formalism (see Bloss 1994, for example). Let us recall that this formalism distinguishes three twin families:

- 1) The ***normal twin*** is associated to a (***hkl***) face which is often the contact (composition) plane. The twin is described as a 180° rotation along an axis perpendicular to this plane.

- 2) The ***parallel twin*** is associated to a 180° twin axis which is a [uvw] crystallographic direction parallel to the contact plane (the composition plane).

- 3) The ***complex twin*** is the combination of one ***parallel twin*** with one ***normal twin***. ***Complex twins*** are often analyzed as twins of twins and not as twins (Boulliard, 2010).

## 2.2 **Twin classification**

**Twins may be classified in three main families following their genesis (Buerger, 1945):**

**- Transformation twins occur following a phase transition. These twins are not rare in feldspars. These twins do not affect the morphology of the crystal which undergoes the transition: they change their internal texture (like the cross-hatched texture due to albite-pericline lamellar twins following the monoclinic-triclinic transition in feldspar).**

**- Mechanical twinning is explained as a shearing mechanism appearing with an external force. These twins may more or less deform the morphology of a single crystal but do not give an external morphology with distinct individuals. The mechanical twins give rise to an internal texture with many parallel twinned lamellae.**

**- The growth twins appear during the growth of the crystal. These twins give rise to morphologies more or less distinct from a single crystal. Since this article is based on morphological analysis, we are dealing only with growth twins. Growth twins occur when there is a “perturbation” during the growth, leading to the so-called “primary**

**twins", or by the oriented attachment of an already formed crystal following precise orientation leading to the so-called "twins by synneusis" (Vance, 1969).**

**Twins by synneusis have the following characteristics: the contact plane is parallel to similar growth faces of the two individuals, and very often one individual is bigger than the other.**

**In primary twins, the different individuals have very often the same sizes: this suggests that the twinning appears at the first stage of growth. The knowledge of the causes of the appearance of such early twins still remains an open question. They might be due to dislocations: it has been demonstrated that dislocations can affect the morphology of quartz crystal leading to twisted crystals (Cordier et al., 2013). Pseudo symmetries and /or existence of polymorphs are favorable situations for the appearance of twins. That concerns feldspars: in addition to the triclinic / monoclinic polymorphs**, it has long been postulated that they **have tetragonal, hexagonal** or cubic pseudo-symmetries (see for example Fedorov, 1902, or Burri, 1962). **Anorthoclase has also two polymorphs: the orthorhombic kumdykolite (Hwang et al., 2009) and the tetragonal lingunite (Sueda et al., 2004). The Al, Si disordering or ordering may affect the twin formation (Laves, 1952). Defects may also be favorable to primary twin formation: it is widely accepted that feldspars may have many defects like exsolution or chemical variations (e.g. Smith, 1974).**

## 3. Materials and methods

### 3.1 **Samples**

The 420 **crystals examined** here are part of the "Collection des minéraux" of the **Institut de Minéralogie, Physique des Matériaux et Cosmochimie (IMPMC)** at the Sorbonne University (SU). They were collected by French volcanologist Haroun Tazieff on the north flank **of Erebus volcano** in 1974, **during the "Mission Antarctique" (CNRS-R.C.P. n° 215, "Mécanismes éruptifs"), as part of the New Zealand Antarctic Program (NZARP)**. When Haroun Tazieff returned to France, more than 400 anorthoclases were given to Serge Wilhelm, a mineralogist at the laboratoire de Minéralogie-Cristallographie de Paris (now IMPMC). This scientist, who was a specialist of feldspars, made a few studies on them (e.g. Clocchiati et al., 1976) but then became more and more involved teaching the history of science. Thereafter, the anorthoclase crystals were stored in drawers and forgotten around 25 years before being rediscovered by one author (J.-C. B.) shortly after the scientist retired. **The**

**samples were** added to **the Sorbonne-Université Collection** in 2000**; o**nly the most scientifically valuable samples were given a catalog number.

We do not know on which criteria Tazieff chose to collect the anorthoclase specimens, but one can assume it was because of their most perfect shape and size, and maybe their unusual twins. The specimens are most likely not representative of all specimens, but rather of the larger, well-shaped and exceptional ones.

The anorthoclases studied here **are quasi systematically macroscopic intergrowths composed of two or more crystals (individuals).** Many of these **intergrowths** are twins. The albite twin, the so-called X-Carlsbad B twin and the Manebach twin were **described by** Mountain (1925). We will revisit these already described twins and document several others. Some **of the twin types** were never reported from **Erebus**; **we also describe two new twin types**.

## 3.2 **Methods**

The **number and percentages** of the different twins have been measured: as mentioned above, they are just indicative. **T**he different shapes and sizes of Carlsbad twins give rise to an evaluation of the re-entrant corner effect.

Since the faces are not flat and the crystals not perfectly formed, the angle measurements cannot be taken with an optical goniometer. They were taken with a contact goniometer: the precision is from one half to two degrees. This poor precision is not a strong drawback: in the great majority of cases the analysis of the habit, the symmetry and the shape can be easily understood without the need of highly precise measurements and give nevertheless unequivocal conclusions.

**A better precision might be achieved with X-ray diffraction patterns, but conclusive patterns are very difficult to get: the crystals are extremely poikolitic (Boudette & Ford, 1966), they have a cross-hatched, "tartan" like, texture due to albite-pericline twin domains (Tagai, 1988) and last but not the least, the twin boundaries are in thick parts of the large crystals (strong X-ray absorption), are often crooked, and therefore difficult to locate with a thin X-ray beam.**

**The Geminography software (Nespolo & Ferraris, 2005, 2006) was used in order to obtain a twin lattice analysis of possible and /or new twins (or hybrid twins). We used version number 2013, released January 18, 2016 found on the website http://crm2.univ-**

**lorraine.fr/geminography/ (on April 3, 2018). The concept of the software is to find a pair of twin elements [uvw] / (hkl). It also gives the parameters of the twin lattice, with the index, n, as well as the obliquity, ω, for a twin. When the twin is not *Friedelian* (n > 6, ω > 6), the software looks for hybrid twins; once successful, it gives the effective index, $n_E$. When none are found, the twin hypothesis should be rejected.**

## 4. Results

### 4.1 **Single crystals habit of anorthoclase**

**Anorthoclase crystals very often exhibit a special habit, which is designated as the “anorthoclase habit” (Deer et al., 2013). This habit is a prism formed by the {110} and $\{1\bar{1}0\}$ pinacoids, the extremities of which are limited by the steep $\{\bar{2}01\}$ pinacoid. Since the $\{1\bar{1}0\}$ faces are more developed than the {110} ones, the small triclinicity is clearly visible. In particular, the $\{\bar{2}01\}$ faces have a parallelogram shape which is quite far from the rhomb shape, expected for monoclinic crystals (fig. 1a-c). Moreover the section of the prism is a parallelogram which is also quite far from a rhomb.**

**Single crystals are common on the slopes of Erebus volcano but very rare in the 420 specimens we analyzed (table 1): this lack of single crystals is certainly a bias introduced by the selected sampling done by Tazieff**. Only 9 single crystals (2%) and 20 **intergrowths** (5%) with a very dominant single crystal **as well as a small individual in Carlsbad twin orientation** have been found. **Five specimens that have an anomalous shape can be added**: some **of their** edges parallel to [001] have disappeared and, instead of a prism, **their** overall shape is lenticular (the {110}, $\{1\bar{1}0\}$ and $\{\bar{2}01\}$ faces still remain) (fig. 1d).

### 4.2 **Symmetrical, asymmetrical, Y shaped and X shaped Carlsbad B twins**

The most frequent twin found **in** Erebus **anorthoclase** appears as a prism with the same section as a single crystal and one re-entrant corner (or angle) at each extremity (fig. 2). This “corner” (or “angle”) is defined as a concave part in the twin due to the intersection of two $(\bar{2}01)$ faces of the two individuals of a twin.

This twin has been so far interpreted as two “single” twins pointing in two opposite directions parallel to [001] (let us recall that the term single twin here refers to twins with two individuals only, it has to be compared to the term multiple twin which refers **to twins with**

**more** individuals). Examples of single twins have been detected, but they are rare (6 specimens have been found). This single twin is a prism associating two individuals, with a re-entrant corner at one extremity and a "salient corner" at the other extremity. This habit will be named the "symmetrical habit" (fig. 3).

The twins with one or two re-entrant corners have been referred to as X-Carlsbad B twins (**Clocchiatti et al., 1976**), which is a source of confusion. **The** characteristics of the Carlsbad, the X and the X-Carlsbad twins are **the following**: the Carlsbad twin is a ***parallel twin*** with the [001] axis as twin element. Two varieties are known: Carlsbad A with (010) as composition plane and Carlsbad B with (100) as composition plane. X twin is a ***normal twin*** with (100) as composition plane (the two-fold axis is perpendicular to this face). The X-Carlsbad B twin is a ***complex twin*** that associates both the X and the Carlsbad twins.

In monoclinic crystals, X and Carlsbad B twins give similar shapes. For triclinic crystals close to monoclinic symmetry, the distinction between the two twins may be very difficult. **The deviation** from monoclinicity **in Erebus anorthoclase** is strongly enhanced by the anisotropy of growth for the {110} pinacoid versus the $\{1\bar{1}0\}$ pinacoid. In that case, the X and the Carlsbad laws do not give the same twin shapes. For the Carlsbad B, the section of the prism is a parallelogram and for the X twin, the section of the prism is a tetragon with a mirror symmetry along one diagonal (fig. 4) (this tetragon is named a "kite" or a deltoid). The analysis of the single twins and the twins with two re-entrant corners unambiguously agrees with a Carlsbad B law and the reference to the X law is unnecessary and wrong.

**The** X term could be used in a different sense for the **shapes** with two re-entrant corners. These **shapes** look like two single Carlsbad B twins, head to foot, i.e. pointing in two opposite directions. Such groups are well known in the gypsum dovetail twins and in the quartz Japan twins (Goldschmidt, 1918, 1923). They can be described as X shaped twins. Hahn et al. (2014) explain **them** with an additional twin law connecting the two single twins. It has been demonstrated that the anorthoclase X shaped groups are not associated to a new twin law but are due to a special growth process (Boulliard, 2010): the "salient corner effect". Due to this effect each individual of a primary single Carlsbad B twin has a tendency to protrude above the salient corner and occupy a space normally occupied by the second twin individual: when this protrusion is symmetrical it gives rise to an oriented association (of two individuals) similar to the X shaped twins of gypsum and quartz. We can therefore conclude that we have X shaped Carlsbad B twins.

In some cases, this salient corner effect is asymmetrical and gives rise to only one well developed crystal on the opposite extremity of the re-entrant corner (it means that there is one re-entrant corner at one extremity and the $(\bar{2}01)$ face of one individual at the other extremity).

We will refer to this habit as the asymmetrical Carlsbad B twin (fig. 5a). A rarer case appears when one crystal on the opposite side of the re-entrant corner grows faster and become big with an anomalously large $(\bar{2}01)$ face. In this case, we get a Y shaped Carlsbad twins (fig. 5b). The asymmetrical and the rare Y shaped Carlsbad twins are a little bit less frequent than the X shaped twins (84 and 100 specimens respectively - see table 1).

**For a long time, the Carlsbad B twin has been a controversial topic: Dowty (1980) stated that this twin requires severe disruptions or distortions at the (100) twin boundary. He made the hypothesis that this twin results of growth factors rather than structural continuity. Wooster (1981) supposed that the composition plane is not a plane but a crenelated interface at the cell scale. Recently, Nespolo and Souvignier (2017) analyzed the substructure of the Carlsbad twin in terms of the (pseudo)-eigensymmetry of the crystallographic orbits for the cases of monoclinic polymorphs. One of their conclusions is that the composition surface is not necessarily (010) and is not even planar. In this last scenario, the result is a penetration twin which is known to be frequent in Carlsbad A twins. Another consequence is that (100) is not excluded as composition plane. In the case of triclinic polymorphs, the common substructure is much less satisfactory. This suggests that the Carlsbad B twin is generated near the transition to monoclinic phase or is inherited from a monoclinic phase.**

### 4.3 **The re-entrant corner effect**

It is **known** since the work of Becke (1911) that the sizes of twins are commonly greater than the neighboring single crystals. These anomalous sizes have been attributed to the presence of the re-entrant corner (or angle).

The re-entrant corner effect in crystal growth was first pointed out by Stranski (1949) for a perfect crystal. He made the hypothesis that the re-entrant corner acts as a step, a most favorable growth site. In other words, the growth in one direction is greatly enhanced by the occurrence of an indestructible step at the twin boundary. Since, this hypothesis has been widely applied. Hartman (1956) has used it and has introduced it in his theory of twinning deduced from the **Periodic Bond Chains (PBC)** vectors theory. Using Lennard-Jones potential function, Boistelle and Aquilano (1978) theoretically demonstrated that the adsorption sites near the re-entrant angles may act as permanent growth sites (step) that leads to the elongated morphology. Later Sunagawa (Sunagawa, 2005 and references therein) have introduced the influences of screw dislocations or the presence of rough faces during the twin growth and made a distinction between the re-entrant corner effect (in its original sense) and the other mechanisms (which finally often lead to quite similar habits). In this article, we will use the term of re-entrant corner effect without specifying if it is used in its original sense or not.

Erebus anorthoclases offer the opportunity to have an evaluation of the re-entrant corner effect thanks to the following reasons:

- There are single (or near single) crystals (without re-entrant corner), asymmetrical Carlsbad B twins (with one re-entrant corner) and X shaped Carlsbad B twins (with two re-entrant corners). **The 6 Y shaped Carlsbad specimens are not here considered, because their anomalous shape seems to be due to a more complex growth process.**
- The crystals and the twins are complete (i.e. without matrix, without missing parts).
- The habits of the single crystals, the asymmetrical Carlsbad twin and X shaped Carlsbad twin are without anomalous growth of faces: the re-entrant corner effect is expected to affect the size only, not the shape.
- The number of specimens is high enough to get pertinent conclusions. There is only one criterion that is not completed: the number of single Carlsbad twins which are not asymmetrical (four unbroken specimens) is too low. So these single “symmetrical” twins are not included in the statistics.

To compare the sizes, we have measured the length in the [010] direction (we call it width, W), the length in the elongated [001] direction (we call it length, L) and the length in the direction perpendicular to the [001] and [010] directions (we call it thickness, T). The average measurements are reported in the table 2.

Let us compare these values and several parameters deduced from them for the following sequence: single crystal, asymmetrical (one re-entrant corner) and X shaped Carlsbad (two re-entrant corners). It appears that the average width and thickness decrease (from 23.6 to 19.6 mm and from 11.7 to 10.3 mm respectively). In consequence the surface of the prism section significantly decreases. The W/T ratio is supposed to be constant because the angles of the prism section are constant so if one knows the W or the T parameter it can deduce the second one. We see in table 2 that the W/T ratio is constant within a range of ±3 % which agrees with the statistical precision. In the meantime the length L increases (from 43.3 to 51 mm). In consequence, the L/W ratio significantly increases from 1.85 (single crystal) to 2.11 (one re-entrant corner) and finally 2.62 (two re-entrant corners). It confirms that the re-entrant corner effect affects the growth rate in the [001] direction. We have also analyzed the L x W x T products which is an indication of the volume of the crystals and/or the twins. This product slowly decreases (around 17% from the single crystal to the X shaped Carlsbad twin).

### 4.4 **Baveno twins**

The Baveno twins are ***normal*** with a (021) twin plane for the right Baveno twin and a $(0\bar{2}1)$ twin plane for the left Baveno twin. We have found 26 specimens exhibiting these twins, **making them the second most frequent twin type after the Carlsbad B twin in our sampling**. The reason why **Baveno twins** have not been **described at Erebus volcano** is **because of their very unusual habit**. With the anorthoclase habit, these twins **are expected** to have a V shape with one (110) or $(\bar{1}10)$ face of one individual quasi parallel to one (110) or $(\bar{1}10)$ face of the second individual. In fact we have observed a Y shape involving in the great majority of cases two Carlsbad B twins. The theoretical angle between the [001] directions of the individuals is equal to ~93° for the left Baveno twin and ~97° for the right Baveno twin. The measured angles agree with these values. Both varieties of these twins have been found (fig. 6).

### 4.5 **Prism twin**

The prism twin (as defined in Deer et al., 1969) is a ***normal twin*** with the (110) plane for the right variety and the $(\bar{1}10)$ plane for the left variety. **According to Smith (1974), this twin has never been observed in triclinic feldspars**. We have found 21 specimens of this twin, 15 of them associate Carlsbad twins and three Carlsbad-single crystals. **The prism** twin appears as one big Carlsbad twin or one big single crystal with an additional smaller Carlsbad twin or one single smaller crystal. The [001] directions of the crystals are parallel and two **$(110)_I$ and $(110)_{II}$ or $(\bar{1}10)_I$ and $(\bar{1}10)_{II}$ planes are (quasi-)parallel (the subscripts indicates each individual - crystal or Carlsbad twin - of the twin). Usually, one individual of this twin is smaller than the other, and only one half or less of the smaller is found**: its [010] direction is quasi perpendicular to a (110) or $(\bar{1}10)$ face of the bigger crystal or twin (fig. 7). **The prism twins look like twins by synneusis: the contact plane is a growth face and the difference of sizes suggests that the crystals have grown separately and that the twin is the result of a late attachment process.**

### 4.6 **Manebach twin**

The Manebach twin is a ***normal twin*** with (001) as **twin** plane. The theoretical angle between the $[001]_I$ and the $[001]_{II}$ directions of the individuals is close to 127.4°. It agrees

**well** with the experimental measured angles which vary from 125 to 130°. This twin is quite rare at Erebus: it represents around 4% (17 specimens) of all the analyzed specimens. **The** shape makes it easy to detect and was described early **by** Mountain (1925).

Two habits may be distinguished: the lengthened and the lenticular habits, which are quasi equally frequent:

- In the elongated habit the two individuals have the usual $\{110\}$, $\{1\bar{1}0\}$, $\{\bar{2}10\}$ faces and very unusual faces, which grow only in these twins. It is the $\{010\}$ faces and a large $(\bar{5}02)$, (fig.8a).
- In the lenticular habit, the twin looks like an optical lens with a flat part (the $(\bar{5}02)$ face) and a convex part **(fig. 8c)**. The shape (the boundary of the large $(\bar{5}02)$ face) is quasi-elliptic or oval with more or less developed straight parts. The convex part of this habit includes poorly defined $(110)$ and $(\bar{1}10)$ faces of the two individuals (the $\{010\}$ faces are missing).

### 4.7 **B or Cunnersdorf twin**

The B twin (Vigier, 1909, Drugman, 1939) also called Cunnersdorf twin (Hintze, 1897) is a ***normal twin*** **with** the $(\bar{2}01)$ **twin** plane. We have found 13 specimens of this twin (6 Carlsbad-Carlsbad and 7 single twins). We may venture that its presence in the anorthoclase crystal is favored because the $(\bar{2}01)$ face is an important face of the anorthoclase habit (in other feldspars this face is very rare).

With the anorthoclase habit it gives rise to a V shape. The angle between the [001] directions along the [010] direction is approximately equal to 70°. The most striking feature of this twin is that the visible $(\bar{2}01)$ faces of two twinned individuals are parallel. It makes this twin very easy to **recognize** (fig. 9).

**We included in this set** 7 specimens that may be described as showing the Cunnersdof twin with one individual poorly developed. With a single crystal, this twin is characterized by a little protruding twinned crystal at one extremity of the prism. With a Carlsbad single twin, the prism is “stopped” by the $(\bar{2}01)$ face of the poorly developed **and flattened** twinned crystal (fig. 9d). **The size difference between the big and the thin individuals, as well as the fact that the contact plane is parallel to a main growth face, suggest that they might be twins by synneusis**.

4.8 **Erebus twin: a newly described twin**

This twin associates two Carlsbad B twins or one Carlsbad B twin and one single crystal (no twins with two single crystals were found). The angle between the [001] directions along an axis close or equal to [010] is very close to 90°: the average experimental measure is equal to 91°35' approximately (fig. 10). We have found 8 Carlsbad-Carlsbad and 5 Carlsbad-single crystal twins. The analysis of the asymmetrical shape (asymmetry from a rhomb) of the $(\bar{2}10)$ faces of both individuals offers the possibility to **discriminate** between a ***normal*** and a ***parallel twin***. It appears that this twin is a ***normal*** one. The composition plane is here $(\bar{3}02)$. This spectacular twin has not yet been described and we **name** it the "Erebus twin".

**The twin lattice analysis with the *Geminography* software (Nespolo & Ferraris, 2005, 2006) gives an index, n, equal to 8 and an obliquity of 2.19°. The high value of n classifies this twin as a *non-Friedelian* twin (n > 6) but remains acceptable for a rare twin. Actually, this twin agrees with the first Friedel's criterion, in terms of frequency and remarkable orientation. It might be reduced with additional studies like the above mentioned case of the Saint-Andrew staurolite.**

4.9 **Tazieff twin: another new twin.**

We found **9 well-defined intergrowths** with a V shape forming an angle of 52° approximately between the [001] directions along the [010] axis (fig. 11). This twin looks like a contact twin. It does not correspond to any reported single twin. Actually Drugman (1938, 1943) has reported the existence of oriented **individuals** of orthoclase with the same 52° angle. He noticed that this twin corresponds to the Emfola (sometimes written Eufola) twin of Des Cloizeaux (1862) who proposed the $(\bar{4}03)$ twin plane. Drugman (1938, 1943) did not agree with this twin law. Instead, he interpreted these associations as twins of twins which he called "cumulative twins". In these twins, which look like single twins, the two individuals, A and C, are oriented by hidden twins: **they** are due, for example, to an A-B twin, a B-C twin and a special growth process which finally hides the B individual. This explanation for the Emfola twin is currently accepted. We have tested the Carlsbad-Manebach cumulative twin (i. e. the A-B twin is a Carlsbad twin and the B-C twin a Manebach twin). It gives rise to **an intergrowth** with a good angle between the [001] directions but it clearly appears that the $(\bar{2}10)$ faces of the individuals I and II have not the same orientations as in our case (fig. 11c).

Nevertheless the angle of 52° is particular: it is very close to the supplementary angle of the angle between the [001] directions found in the Manebach twin. Let us recall here that one fundament of the twin theory (e.g. Friedel, 1904) states that if there is a ***normal twin*** involving a crystallographic (***hkl***) plane, there is another twin (called a corresponding twin) which is a ***parallel twin*** involving a crystallographic [*uvw*] axis. The orientation of the [*uvw*] axis is close to the direction perpendicular to the (***hkl***) plane. Examples of corresponding twins are not very frequent: the most quoted are the albite and pericline twins (Deer et al., **2013**). Let us consider now the Manebach twin which is a ***normal twin*** with the (001) plane. The closest direction perpendicular to this plane is **[205]**. This direction is a candidate for the axis of the corresponding ***parallel twin*** of the Manebach twin. The analysis of the asymmetrical shapes of the ($\bar{2}01$) faces on the only one specimen associating two single crystals (fig. 11) shows that the $(\bar{2}01)_I$ and $(\bar{2}01)_{II}$ faces of both individuals are deduced by a rotation parallel to the composition plane and at least quasi parallel to the **[205]** direction.

The 52° V twin is well analyzed as a ***parallel twin*** with the **[205]** axis and a composition plane close to ($\bar{5}02$). This high index face has been already mentioned as a likely compensation face in the Manebach twin, and since it appears here again, one may conjecture that this face could appear as a growth face in anorthoclase. **The twin lattice analysis gives an index, n, equal to 5 and an obliquity of 2.88°, which classifies this twin as a *Friedelian* twin (n ≤ 6; ω ≤ 6).**

This twin is the first example of the corresponding twin of the Manebach twin. We propose to name it "Tazieff twin" in honor of this famous volcanologist who collected the anorthoclase specimens.

### 4.10 **Albite twin**

The albite twin is a ***normal twin*** with the (010) plane. Mountain (1925) has detected it on single crystals with a very rounded shape (the type I crystal following his classification). This twin appears as thin lamellae that were detected with the microscope in thin sections. It does not appear clearly on the shape of the crystals. Six crystals, with rounded and flat shapes close to the description of the Mountain's type I crystals, exhibit smooth striae on the {110} and/or {$\bar{1}10$} faces and parallel to [001], which agrees with well-developed albite twins (fig. 12).

### 4.11 **Single and near single intergrowths: rare or questionable to doubtful twins**

The recurrent question about the analysis of a great number of varied **intergrowths** of crystals is to make the distinction between twins and accidental **intergrowths**. This question has spelt trouble since the middle of the 19$^{th}$ century and makes the analysis of twins quite difficult.

For the remaining oriented **intergrowths** found on Erebus (around 50 specimens excluding indistinct or broken specimens) we have tested all the known twin laws (32). We have also tested some possible twin laws. We have not tested ***complex twins*** or ***twins of twins***. In several cases an acceptable match **was** found. In the best cases of oriented **intergrowths**, it was tempting to present them as twins but we have imposed ourselves that the confirmation of a twin needs at least 5 specimens with the same precise orientation. In the other cases, the lack of clear symmetry or variations around a suspected orientation forbids to suspect a twin law. We give hereafter the results of these additional classifications, with less than five specimens per category.

- $[\bar{1}12]$ Nevada twin (Drugman, 1938): 2 specimens are in good agreement and 3 specimens are suspected (poor angular precision). **The twin lattice analysis gives a *non-Friedelian* twin; the indices, n, deduced from the 7 different perpendicular planes are in between 6 and 15, with an obliquity, ω, between 5.71 and 1.22 respectively. With the same software, this could be interpreted as a hybrid twin; then the effective twin index $n_E$ is 2.2.**
- $[\bar{4}30]$ twin (unnamed but quoted in Hintze, 1897): in a set of 12 specimens, some **intergrowths seem to follow this law, some others with the close $[\bar{2}10]$ law and the last specimens** with axis close to the $[\bar{4}31]$ axis. **Analysis gives indices, n, between 9 and 20 with obliquities, ω, between 5.8 and 3.2 respectively. These twins seem therefore highly improbable. Consequently** the reference to this twin law is more descriptive than confirmed.
- $(\bar{1}\bar{1}2)$ or $(\bar{1}12)$ Goodsprings twins: Drugman (1938) has proposed this “twin” law as descriptive: he did not confirm it, but noticed that a significant number of feldspar intergrowths found in Goodsprings, Nevada, might be approximately described with this “law”. We found 5 specimens that might be more or less described with this “descriptive twin law”. **The twin lattice analysis confirmed that this twin is unlikely (n= 19).**
- $(1\bar{1}1)$ Breithaupt twin (see Hintze 1897): 3 specimens approximately agree. **The twin lattice analysis gives a *Friedelian* twin, with n= 3 and ω = 1.03.**
- (130) (see Smith 1974): one specimen with a prismatic shape and a triangular section agrees. **The twin lattice analysis gives a *Friedelian* twin, with n= 3 and ω = 2.50.**
- (320) or $(3\bar{2}0)$ (mentioned by Gates, 1953, but not confirmed): one specimen well agrees. **The twin lattice analysis recognized these twins are unlikely (n = 14).**

For some intergrowths, their status (***normal*** or ***parallel twin***) is not well defined:

- (203), i.e. the Vigier's A twin (1909, known in one specimen): one specimen agrees. **The twin lattice analysis recognized that this twin is unlikely (n between 9 and 13 and ω between 3.88 and 3.32 respectively). Even with the hybrid analysis, the software gives a $n_E$ of 6.5.**

- (092) twin (Vigier, 1909): 2 doubtful cases found. **The analysis does not find any lattice twin.**

- A $(1\bar{1}2)$ new twin law has been suspected **in** 2 specimens. **The twin lattice analysis gives indices, n, between 7 and 15 with obliquities, ω, between 4.42 and 1.09 respectively. It could also be interpreted as a hybrid twin; then the effective twin index $n_E$ is 2.7.**

For the remaining **intergrowths** of crystals (18 specimens excluding indistinct or broken specimens), no remarkable orientations were found and they are certainly accidental **intergrowths**.

## 5. Conclusion

Anorthoclase crystals **were erupted in volcanic bombs and were eroded out to form a lag of near perfect crystals**. The great number of crystals and **intergrowths** of crystals found without matrix in the flank of Erebus volcano has given the opportunity to describe them precisely. This is the case of the previously named X-Carlsbad B twin, which is actually a Carlsbad B twin. As shown **here,** the number of twins and their shapes in this locality are uncommon. One may conjecture that the analysis of a greater number (i.e. far more than 420) of **intergrowths** will certainly **allow** other twins **to be recognized**. We have found two new twins that we **name** Erebus and Tazieff twins. The Tazzief twin is found to be the corresponding twin of the Manebach twin, which was theoretically predicted but never found. We have demonstrated that the Tazieff twin is not the Carlsbad-Manebach twin of twin (also known as the Emfola twin). One may suggest that the status of the Emfola twin will need additional studies.

One of the main features of anorthoclase twins **from Erebus volcano** is that they reveal importance of the (***h0k***) faces in several twins (Carlsbad B, Manebach, Cunnersdorf, Tazieff and Erebus).

The great number of twins also permits the relative abundance of the different kinds and varieties of twins and their shapes **to be determined**. Our results show that the Erebus anorthoclases give rise to a good estimation of the re-entrant corner effect. As far as we know, there is no other example of such estimation, and the Erebus crystals and twins might be an empirical support for future theoretical investigations about this effect.

In conclusion, the shapes and varieties of twins of the Erebus anorthoclase are quite surprising and give **an** unprecedented improvement in **the** knowledge of feldspar twins. Such knowledge is very important since feldspar crystals, twins and their relative sizes should affect some characteristics in materials like rocks and ceramics.


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**Table 1: Summary on the different anorthoclase shapes, intergrowths and twins, over the set of 420 specimens.**

| | |
|---|---|
| **Single crystals or near single crystals** : 8.1%<br>- Single crystal: 9<br>- Single crystal with small Carlsbad twin: 20<br>- Anomalous lenticular shape : 5 | **Manebach twins** : 4%<br>Elongated: 7<br>Lenticular: 8<br>Broken: 2 |
| **Albite twins** : 6 (1.4%) | **Carlsbad-B twins**: 21.4%<br>Simple “arrow head” Carlsbad B twin: 6<br>Asymmetrical Carlsbad twin: 78<br>Y shaped Carlsbad twin: 6 |
| **X shaped Carlsbad-B twins**: 100 (23.8%) | **G or Cunnersdorf twins**: 4.8%<br>- Carlsbad-Carlsbad twin: 6<br>- Single crystals: 7<br>- Lamellar part: 7 |
| **Tazieff twins**: 2.1%<br>- Carlsbad-Carlsbad twin: 6<br>- Single crystal-Carlsbad twin: 3 | **Erebus twin**: 3.1%<br>- Carlsbad-Carlsbad twins: 8<br>- Single crystal-Carlsbad twin: 5 |
| **Baveno twins**: 6.2%<br>- Carlsbad-Carlsbad twin: 24<br>- Single crystal-Carlsbad twin: 2 | **Prism twins**: 5%<br>- Carlsbad-Carlsbad twin: 15<br>- Single crystal-Carlsbad twin: 3<br>- With other twins: 3 |
| **Rare, suspected or doubtful twins**: 30 (7.1%) | **Other single intergrowths**: 18 (4.3%) |
| **Confused and indistinct intergrowths**: 18 (4.3%) | **Broken indistinct parts**: 18 (4.3%) |

**Table 2: Statistics on the size of Erebus volcano single crystals and Carlsbad B twins.** W, T and L are measured in millimeters (the number of specimens is lower than the number of specimens reported in table 1 because some of them are broken, **the ranges of length are indicated between the square brackets and the standard deviation $\sigma_{n-1}$ in parenthesis**).

| | Average width W | Average thickness T | Average length L | Average L/W ratio | Average W/T ratio | Average LxWxT($x10^{-4}$) |
|---|---|---|---|---|---|---|
| Single or near single crystal 25 specimens | 23.5<br>[11-30]<br>(5.4) | 11.7<br>[8.1-15.5]<br>(2.3) | 43.3<br>[18-60]<br>(9.8) | 1.85<br>(0,25) | 2.02 | 1.19 |
| Asymmetrical Carlsbad twin 36 specimens | 21.4<br>[11-32]<br>(6.5) | 11.11<br>[7.4-16.8]<br>(3.0) | 45<br>[20-65]<br>(11.8) | 2.11<br>(0,4) | 1.93 | 1.07 |
| X-shaped Carlsbad twin 40 specimens | 19.8<br>[8-32]<br>(5,6) | 10.1<br>[4-14.7]<br>(2,4) | 51<br>[27-75]<br>(11.8) | 2.62<br>(0,4) | 1.92 | 1.02 |

## Figure captions*

*** # referred to catalogue number, size is: length of the biggest individual x twin or individual width x twin or individual thickness.**

Figure 1: (a) Single crystal photo (#13528, 32.5 x 14.6 x 9.1 mm), (b) single crystal sketch, (c) single crystal [010] side view and (d) rounded habit. (#13527, 32.9 x 21.7 x 8.1 mm).

Figure 2: (a) X shaped Carlsbad **B** twin, the previously called X Carlsbad B twin (#13529, 68.9 x 24.4 x 13.6 mm), (b) sketch.

Figure 3: Symmetrical Carlsbad B single twin, (a) photo, (b) sketch (#13533, 31.5 x 12.9 x 7.0 mm).

Figure 4: (a) Section expected for a Carlsbad B twin, (b) section expected for an X twin, The $V_1$ and $V_2$ vectors illustrate the different face growth speeds (c) observed section in agreement with Carlsbad B twin **(#13568, 20 x 12 mm)**.

Figure 5: (a) Asymmetrical Carlsbad B single twin (#13534, 56.6 x 23.7 x 11.6 mm), (b) Y shaped Carlsbad B single twin (#13531, 64.4 x 35.4 x 15.5 mm).

Figure 6: Baveno twin, (a) photo, (b) sketch (#13535, 39.9 x 38.9 x 9.2 mm).

Figure 7: Prism (110) twin (#13543, 49.4 x 18.3 x 10.8 mm), (a) photo, (b) theoretical sketch showing the orientation of both individuals (view along [001]).

Figure 8: Manebach twin, (a) lengthened habit (#13538, 65.3 x 17.7 x 17.5 mm), (b) theoretical sketch, (c) lenticular habit (#13537, 55.5 x 37.4 x 14.4 mm).

Figure 9: Cunnersdorf twin, (a) sketch, (b) single crystal-single crystal (#13539, 24.9 x 14.3 x 14.3 mm), (c) Carlsbad-Carlsbad (#13540, 40.4 x 21.6 x 27.5 mm), (d) **the right end with one face is due to a flattened individual in Cunnersdorf twin orientation**. (#13541, 43.4 x 19.3 x 11.6 mm).

Figure 10: The newly described Erebus twin, (a) photo (here single crystals, #13545, 47.5 x 23.4 x 24.8 mm), (b) sketch.

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Figure 11: The newly described Tazieff twin, (a) photo (#13542, 24.3 x 14.5 x 14.1 mm), (b) sketch and, (c) theoretical sketch of the cumulative Carlsbad-Manebach twin, here the 1 and 3 individuals (the ($\bar{2}$10) faces of the 1 and 3 individuals do not have the same orientations as in (b)).

Figure 12: **This rounded shaped crystal is attributed to an albite twin (Mountain, 1925)** (#13532, 35.6 x 33.3 x 10.9 mm).

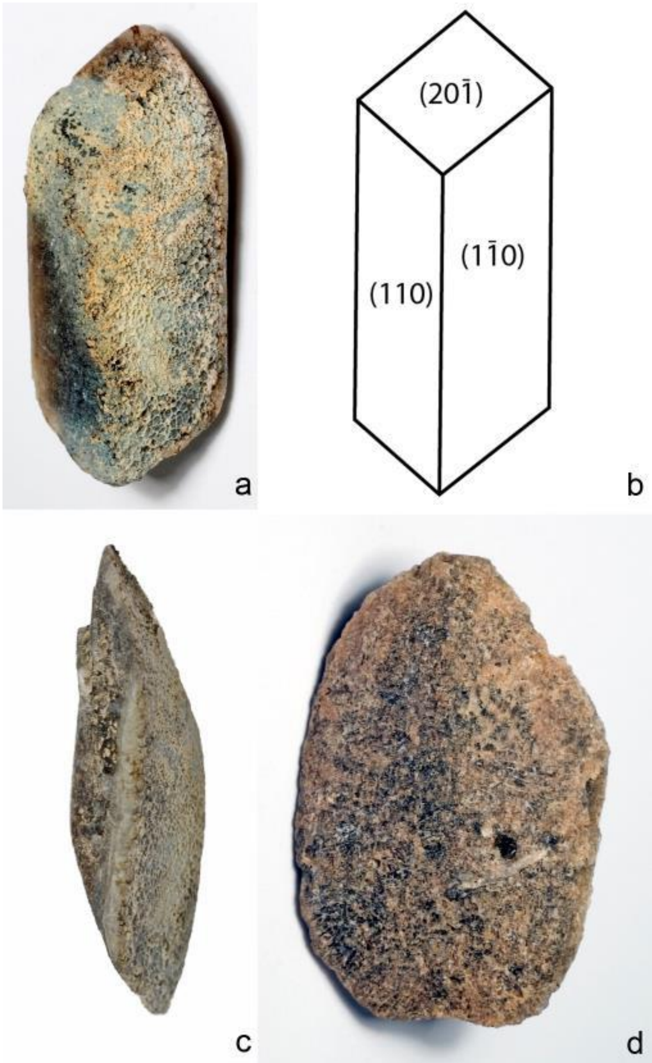


Figure 1: (a) Single crystal photo (#13528, 32.5 x 14.6 x 9.1 mm), (b) single crystal sketch, (c) single crystal [010] side view and (d) rounded habit. (#13527, 32.9 x 21.7 x 8.1 mm).

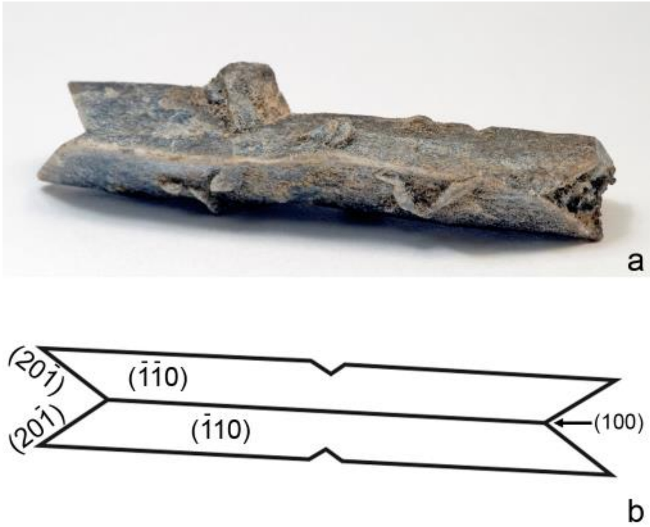


Figure 2: (a) X shaped Carlsbad **B** twin, the previously called X Carlsbad B twin (#13529, 68.9 x 24.4 x 13.6 mm), (b) sketch.

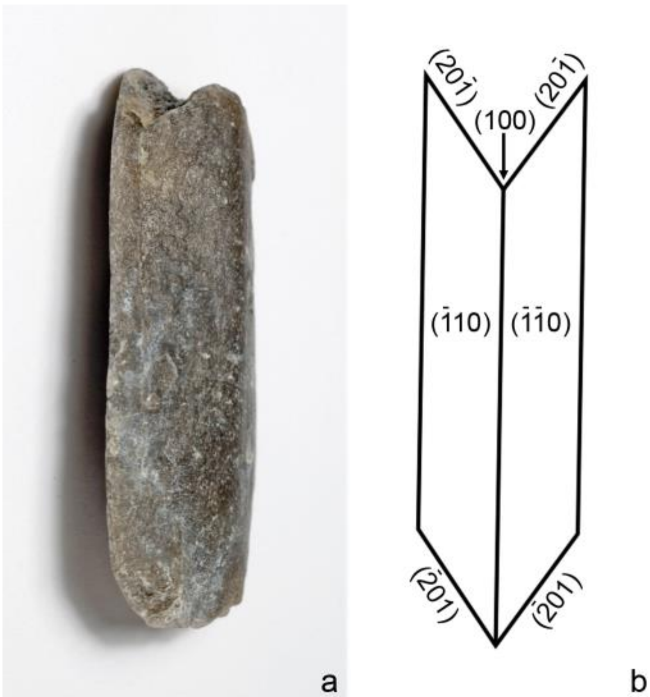


Figure 3: Symmetrical Carlsbad B single twin, (a) photo, (b) sketch (#13533, 31.5 x 12.9 x 7.0 mm).

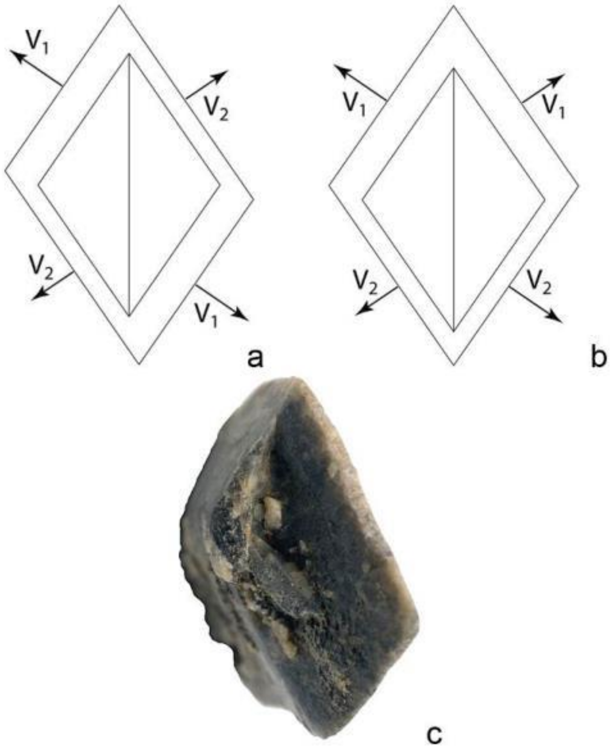


Figure 4: (a) Section expected for a Carlsbad B twin, (b) section expected for an X twin, The $V_1$ and $V_2$ vectors illustrate the different face growth speeds (c) observed section in agreement with Carlsbad B twin **(#13568, 20 x 12 mm)**.


Figure 5: (a) Asymmetrical Carlsbad B single twin (#13534, 56.6 x 23.7 x 11.6 mm), (b) Y shaped Carlsbad B single twin (#13531, 64.4 x 35.4 x 15.5 mm).

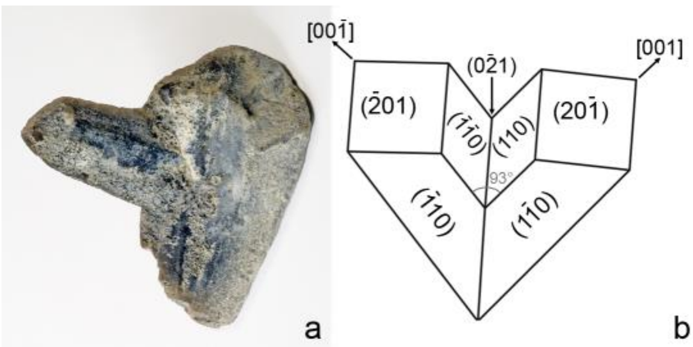


Figure 6: Baveno twin, (a) photo, (b) sketch (#13535, 39.9 x 38.9 x 9.2 mm).

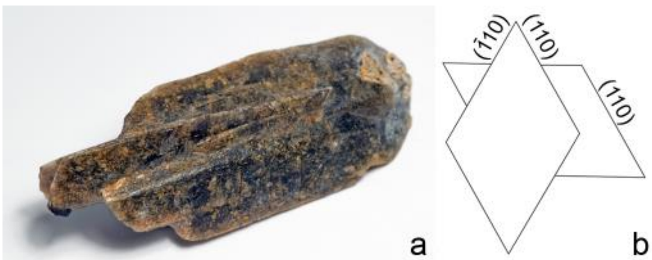


Figure 7: Prism (110) twin (#13543, 49.4 x 18.3 x 10.8 mm), (a) photo, (b) theoretical sketch showing the orientation of both individuals (view along [001]).

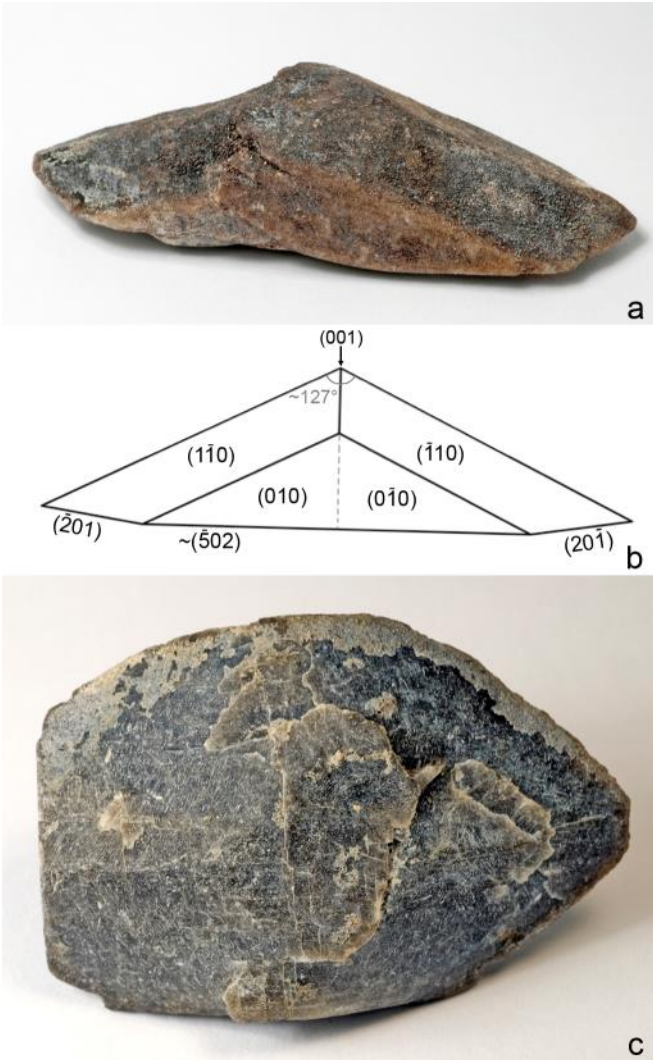


Figure 8: Manebach twin, (a) lengthened habit (#13538, 65.3 x 17.7 x 17.5 mm), (b) theoretical sketch, (c) lenticular habit (#13537, 55.5 x 37.4 x 14.4 mm).

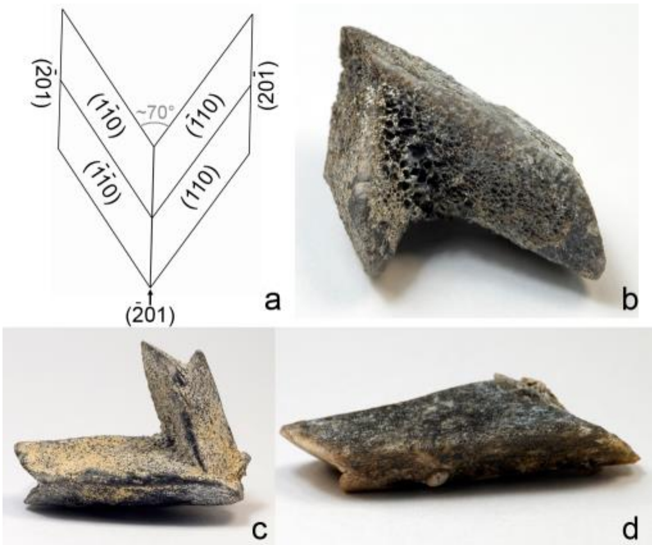

Figure 9: Cunnersdorf twin, (a) sketch, (b) single crystal-single crystal (#13539, 24.9 x 14.3 x 14.3 mm), (c) Carlsbad-Carlsbad (#13540, 40.4 x 21.6 x 27.5 mm), (d) **the right end with one face is due to a flattened individual in Cunnersdorf twin orientation.** (#13541, 43.4 x 19.3 x 11.6 mm).

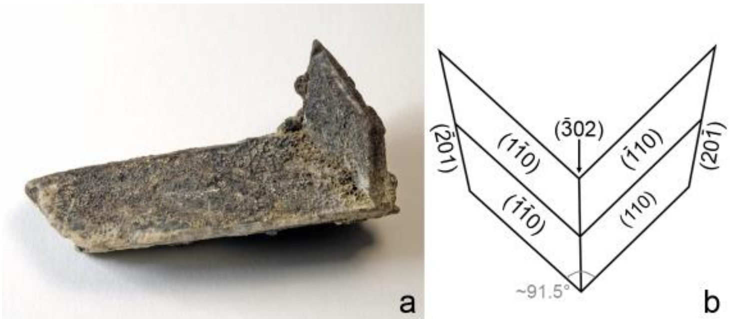


Figure 10: The newly described **Erebus** twin, (a) photo (here single crystals, #13545, 47.5 x 23.4 x 24.8 mm), (b) sketch.

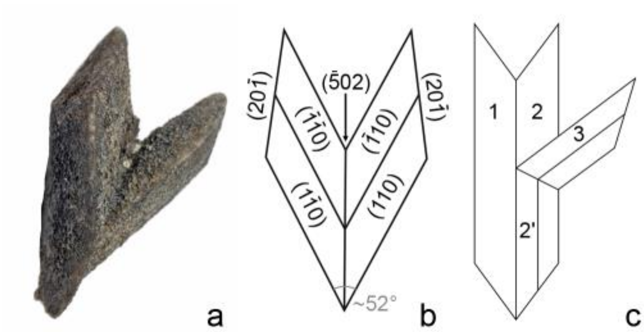


Figure 11: The newly described Tazieff twin, (a) photo (#13542, 24.3 x 14.5 x 14.1 mm), (b) sketch and, (c) theoretical sketch of the cumulative Carlsbad-Manebach twin, here the 1 and 3 individuals (the $(\bar{2}10)$ faces of the 1 and 3 individuals do not have the same orientations as in (b)).


Figure 12: **This rounded shaped crystal is attributed to an albite twin (Mountain, 1925)** (#13532, 35.6 x 33.3 x 10.9 mm).