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

Jean-Claude Boulliard, Eloise Gaillou

► **To cite this version:**

Jean-Claude Boulliard, Eloise Gaillou. Twinning in anorthoclase megacrysts from phonolitic eruptions, Erebus volcano, Antarctica. *European Journal of Mineralogy*, 2019, 31 (1), pp.99-110. <10.1127/ejm/2019/0031-2804>. <hal-02335379>

HAL Id: hal-02335379

<https://hal.science/hal-02335379v1>

Submitted on 28 Oct 2019

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Title:

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

Running title: Anorthoclase twins at Erebus volcano (Antartica)

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36 **Twinning in anorthoclase megacrysts from phonolitic eruptions, Erebus**
37 **volcano, Antarctica**

38
39
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47
48 **Abstract**

49
50 Anorthoclase is a **major** component of **in trachytic and phonolitic lavas**. Mount
51 Erebus volcano is well known for its anorthoclase **megacrysts which show a range of twin**
52 **morphologies. Thanks to a set of more than 400 specimens collected by volcanologist**
53 **Haroun Tazieff, we have revisited and improved the knowledge about the twins from**
54 **this locality, and documented the crystals' shapes, sizes and frequencies.** The status of the
55 X Carlsbad B twin **is revised.** Several twins, not yet mentioned **from this locality, are**
56 **identified.** Two new **types of twins** (referred to here as Erebus and Tazieff) **are described,**
57 **extending our knowledge of twins.**

58
59 **Keywords**

60 **Twin crystal; anorthoclase; feldspar; Erebus; Carlsbad twin; Erebus twin; Tazieff twin.**
61

62 **1. Introduction**

63 Mount Erebus (3794 m) on Ross Island (Antarctica) is a continuously active volcano with
64 a permanent phonolite lava lake. **Petrologically, Mount Erebus evolved over 1.3 million**
65 **years from basanites to anorthoclase-rich phonolite now being erupted** (e.g. Kyle et al.,
66 1992; Kelly et al., 2008, Esser et al., 2004).

67
68 The **younger phonolitic** geochemical history of the volcano has been thoroughly
69 **documented and shows that the phonolitic composition has been stable for over the last**

70 **10,000 years (Caldwell and Kyle, 1994, Kelly et al., 2008, Sims et al. 2008, 2013, Iverson**
71 **et al., 2014).**

72

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

85 Mount Erebus anorthoclases show remarkable oscillatory zoning (Kyle, 1977;
86 Caldwell & Kyle, 1994; **Dunbar** et al., 1994; Kelly et al., 2008; Moussallam et al., 2015).
87 Analyses **by Kelly et al. (2008) of 8 anorthoclase crystals in bombs erupted in 1985 show**
88 **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
89 al. (2015) explained **the** oscillatory composition and zoning by **circulation of** the
90 anorthoclase crystals **in** the plumbing system and over distances of up to several kilometers.
91 They estimated that 1-cm wide anorthoclase crystals are at least 14 years old and **probably**
92 record cycles **from a deeper magma chamber** up to the lava lake. The lattice parameters of
93 the Erebus anorthoclase (triclinic) crystals measured by Carmichael and MacKenzie (1964),
94 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
95 slawsonite (Sr end-member)) are:
96 $a = 8.263 \text{ \AA}, b = 12.935 \text{ \AA}, c = 7.138 \text{ \AA}$ and $\alpha = 92^\circ 15', \beta = 116^\circ 19', \gamma = 90^\circ 10'$ (b being the
97 parameter in the direction that corresponds to the binary axis in monoclinic feldspars, **the**
98 **authors did not include error limits).** Other physical properties are discussed by
99 **Boudette and Ford (1969).** We refer to **Mason et al. (1982)** for trace element contents in
100 **Erebus anorthoclase.**

101

102 The specimens of this study were collected by the French volcanologist Haroun Tazieff
103 in 1974. While anorthoclase crystals **have been** largely studied to understand their

104 geochemical changes at Mount Erebus volcano, they are here examined to better constrain
105 their twinning.

106

107

108 **2. State of the art: Feldspar and twins**

109 **2.1 Twin definitions**

110 **A twin is defined as an intergrowth (an edifice) of two (or more) homogeneous**
111 **similar crystals (called individuals), in which the two adjacent individuals have different**
112 **orientations, characterized by a geometrical operation called *twin operation*. The**
113 **difference between an accidental intergrowth and a twin is based on several criteria.**
114 **The first one postulated by Friedel (1904) is that the edifice suspected to be a twin must**
115 **be more or less frequent, or that the suspected twin (crystallographic) operation is**
116 **remarkable. Friedel also developed the so-called “*reticular theory*” which postulates**
117 **there is a sublattice, called *twin lattice* shared by the two individuals. This sublattice has**
118 **a lattice element (plane or axis) on which the twin operation occurs and a lattice element**
119 **(axis or plan) (quasi)-perpendicular to it. These two elements define the cell of the**
120 **sublattice. The ratio of the mesh volume of the twin lattice on the mesh volume of the**
121 **unit cell of the individual is the *twin index*, n . It indicates the degree of lattice restoration**
122 **between the twin individuals sharing a partially coherent interface (composition plane).**
123 **When the two elements are not perpendicular (pseudo-symmetry) the deviation angle**
124 **from perpendicularity, ω , is called *obliquity*. On the basis of his life work on twins,**
125 **Friedel has established the empirical criteria: $n \leq 6$ and $\omega \leq 6$. Twins following these**
126 **limits are now called *Friedelian twins* (e.g. Nespolo & Ferraris, 2005, 2006). To explain**
127 **some *non Friedelian twins*, some authors (Nespolo & Ferraris, 2005, 2009; Pignatelli et**
128 **al., 2011) have elaborated an extension of the reticular theory with the *hybrid twins* in**
129 **which two or more twin sublattices exist. The overall lattice restoration is measured by**
130 **the effective twin index, n_E , an extension of n . Since this index does not explain the**
131 **frequency of some twins, the reticular theory has been improved by Marzouki et al.**
132 **(20014a), by taking into account symmetries inside the crystal cell, i.e. the (pseudo-**
133 **)eigensymmetry of crystallographic orbits. These authors (Marzouki et al., 2014b) have**
134 **analyzed the eigensymmetries of the most common Saint–Andrew staurolite twin ($n_E = 6$**
135 **from $n = 12$) and found that the anion sublattice is restored by the twin law and that the**
136 **cation restoration in the Saint-Andrew twin is better than in other staurolite twins.**

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

142
143

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

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

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

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

155

156 2.2 Twin classification

157 **Twins may be classified in three main families following their genesis (Buerger,**
158 **1945):**

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

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

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

171 **twins”, or by the oriented attachment of an already formed crystal following precise**
172 **orientation leading to the so-called “twins by synneusis” (Vance, 1969).**
173 **Twins by synneusis have the following characteristics: the contact plane is parallel to**
174 **similar growth faces of the two individuals, and very often one individual is bigger than**
175 **the other.**
176 **In primary twins, the different individuals have very often the same sizes: this suggests**
177 **that the twinning appears at the first stage of growth. The knowledge of the causes of the**
178 **appearance of such early twins still remains an open question. They might be due to**
179 **dislocations: it has been demonstrated that dislocations can affect the morphology of**
180 **quartz crystal leading to twisted crystals (Cordier et al., 2013). Pseudo symmetries and**
181 **/or existence of polymorphs are favorable situations for the appearance of twins. That**
182 **concerns feldspars: in addition to the triclinic / monoclinic polymorphs, it has long been**
183 **postulated that they have tetragonal, hexagonal or cubic pseudo-symmetries (see for**
184 **example Fedorov, 1902, or Burri, 1962). Anorthoclase has also two polymorphs: the**
185 **orthorhombic kumdykolite (Hwang et al., 2009) and the tetragonal lingunite (Sueda et**
186 **al., 2004). The Al, Si disordering or ordering may affect the twin formation (Laves,**
187 **1952). Defects may also be favorable to primary twin formation: it is widely accepted**
188 **that feldspars may have many defects like exsolution or chemical variations (e.g. Smith,**
189 **1974).**

190

191 **3. Materials and methods**

192 **3.1 Samples**

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

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

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

210
211 The anorthoclases studied here **are quasi systematically macroscopic intergrowths**
212 **composed of two or more crystals (individuals)**. Many of these **intergrowths** are twins.
213 The albite twin, the so-called X-Carlsbad B twin and the Manebach twin were **described by**
214 Mountain (1925). We will revisit these already described twins and document several others.
215 **Some of the twin types** were never reported from **Erebus**; **we also describe two new twin**
216 **types**.

217

218 3.2 Methods

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

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

228 **A better precision might be achieved with X-ray diffraction patterns, but conclusive**
229 **patterns are very difficult to get: the crystals are extremely poikilitic (Boudette & Ford,**
230 **1966), they have a cross-hatched, “tartan” like, texture due to albite-pericline twin**
231 **domains (Tagai, 1988) and last but not the least, the twin boundaries are in thick parts**
232 **of the large crystals (strong X-ray absorption), are often crooked, and therefore difficult**
233 **to locate with a thin X-ray beam.**

234

235 **The Geminography software (Nespolo & Ferraris, 2005, 2006) was used in order to**
236 **obtain a twin lattice analysis of possible and /or new twins (or hybrid twins). We used**
237 **version number 2013, released January 18, 2016 found on the website [Page 7 \(Boulliard\)](http://crm2.univ-</p></div><div data-bbox=)**

238 lorraine.fr/geminography/ (on April 3, 2018). The concept of the software is to find a
239 pair of twin elements $[uvw] / (hkl)$. It also gives the parameters of the twin lattice, with
240 the index, n , as well as the obliquity, ω , for a twin. When the twin is not *Friedelian* ($n >$
241 6 , $\omega > 6$), the software looks for hybrid twins; once successful, it gives the effective index,
242 n_E . When none are found, the twin hypothesis should be rejected.

243

244

245 4. Results

246

247 4.1 Single crystals habit of anorthoclase

248 Anorthoclase crystals very often exhibit a special habit, which is designated as the
249 “anorthoclase habit” (Deer et al., 2013). This habit is a prism formed by the $\{110\}$ and $\{1$
250 $\bar{1}0\}$ pinacoids, the extremities of which are limited by the steep $\{\bar{2}01\}$ pinacoid. Since the
251 $\{1\bar{1}0\}$ faces are more developed than the $\{110\}$ ones, the small triclinicity is clearly
252 visible. In particular, the $\{\bar{2}01\}$ faces have a parallelogram shape which is quite far from
253 the rhomb shape, expected for monoclinic crystals (fig. 1a-c). Moreover the section of
254 the prism is a parallelogram which is also quite far from a rhomb.

255 Single crystals are common on the slopes of Erebus volcano but very rare in the 420
256 specimens we analyzed (table 1): this lack of single crystals is certainly a bias introduced
257 by the selected sampling done by Tazieff. Only 9 single crystals (2%) and 20 intergrowths
258 (5%) with a very dominant single crystal as well as a small individual in Carlsbad twin
259 orientation have been found. Five specimens that have an anomalous shape can be added:
260 some of their edges parallel to $[001]$ have disappeared and, instead of a prism, their overall
261 shape is lenticular (the $\{110\}$, $\{1\bar{1}0\}$ and $\{\bar{2}01\}$ faces still remain) (fig. 1d).

262

263

264 4.2 Symmetrical, asymmetrical, Y shaped and X shaped Carlsbad B twins

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

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

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

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

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

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

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

307 We will refer to this habit as the asymmetrical Carlsbad B twin (fig. 5a). A rarer case appears
308 when one crystal on the opposite side of the re-entrant corner grows faster and become big
309 with an anomalously large ($\bar{2}01$) face. In this case, we get a Y shaped Carlsbad twins (fig.
310 5b). The asymmetrical and the rare Y shaped Carlsbad twins are a little bit less frequent than
311 the X shaped twins (84 and 100 specimens respectively - see table 1).

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

325
326

327 4.3 The re-entrant corner effect

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

331 The re-entrant corner effect in crystal growth was first pointed out by Stranski (1949) for a
332 perfect crystal. He made the hypothesis that the re-entrant corner acts as a step, a most
333 favorable growth site. In other words, the growth in one direction is greatly enhanced by the
334 occurrence of an indestructible step at the twin boundary. Since, this hypothesis has been
335 widely applied. Hartman (1956) has used it and has introduced it in his theory of twinning
336 deduced from the **Periodic Bond Chains (PBC)** vectors theory. Using Lennard-Jones
337 potential function, Boistelle and Aquilano (1978) theoretically demonstrated that the
338 adsorption sites near the re-entrant angles may act as permanent growth sites (step) that leads
339 to the elongated morphology. Later Sunagawa (Sunagawa, 2005 and references therein) have
340 introduced the influences of screw dislocations or the presence of rough faces during the twin

341 growth and made a distinction between the re-entrant corner effect (in its original sense) and
342 the other mechanisms (which finally often lead to quite similar habits). In this article, we will
343 use the term of re-entrant corner effect without specifying if it is used in its original sense or
344 not.

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

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

360

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

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

376 products which is an indication of the volume of the crystals and/or the twins. This product
377 slowly decreases (around 17% from the single crystal to the X shaped Carlsbad twin).

378

379 4.4 Baveno twins

380 The Baveno twins are *normal* with a (021) twin plane for the right Baveno twin and a
381 (0 $\bar{2}$ 1) twin plane for the left Baveno twin. We have found 26 specimens exhibiting these
382 twins, **making them the second most frequent twin type after the Carlsbad B twin in our**
383 **sampling.** The reason why **Baveno twins** have not been **described at Erebus volcano** is
384 **because of their very unusual habit.** With the anorthoclase habit, these twins **are expected**
385 to have a V shape with one (110) or ($\bar{1}$ 10) face of one individual quasi parallel to one (110) or
386 ($\bar{1}$ 10) face of the second individual. In fact we have observed a Y shape involving in the great
387 majority of cases two Carlsbad B twins. The theoretical angle between the [001] directions of
388 the individuals is equal to $\sim 93^\circ$ for the left Baveno twin and $\sim 97^\circ$ for the right Baveno twin.
389 The measured angles agree with these values. Both varieties of these twins have been found
390 (fig. 6).

391

392 4.5 Prism twin

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

406

407 4.6 Manebach twin

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

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

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

415 - In the elongated habit the two individuals have the usual $\{110\}$, $\{1\bar{1}0\}$, $\{\bar{2}10\}$ faces
416 and very unusual faces, which grow only in these twins. It is the $\{010\}$ faces and a large $(\bar{5}$
417 $02)$, (fig.8a).

418 - In the lenticular habit, the twin looks like an optical lens with a flat part (the $(\bar{5}02)$
419 face) and a convex part (**fig. 8c**). The shape (the boundary of the large $(\bar{5}02)$ face) is quasi-
420 elliptic or oval with more or less developed straight parts. The convex part of this habit
421 includes poorly defined (110) and $(\bar{1}10)$ faces of the two individuals (the $\{010\}$ faces are
422 missing).

423

424 4.7 B or Cunnersdorf twin

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

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

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

441

442 4.8 Erebus twin: a newly described twin

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

451 **The twin lattice analysis with the *Geminography* software (Nespolo & Ferraris,**
452 **2005, 2006) gives an index, n, equal to 8 and an obliquity of 2.19°. The high value of n**
453 **classifies this twin as a *non-Friedelian* twin (n > 6) but remains acceptable for a rare**
454 **twin. Actually, this twin agrees with the first Friedel’s criterion, in terms of frequency**
455 **and remarkable orientation. It might be reduced with additional studies like the above**
456 **mentioned case of the Saint-Andrew staurolite.**

457

458 4.9 Tazieff twin: another new twin.

459 We found **9 well-defined intergrowths** with a V shape forming an angle of 52°
460 approximately between the [001] directions along the [010] axis (fig. 11). This twin looks like
461 a contact twin. It does not correspond to any reported single twin. Actually Drugman (1938,
462 1943) has reported the existence of oriented **individuals** of orthoclase with the same 52°
463 angle. He noticed that this twin corresponds to the Emfola (sometimes written Eufola) twin of
464 Des Cloizeaux (1862) who proposed the ($\bar{4}03$) twin plane. Drugman (1938, 1943) did not
465 agree with this twin law. Instead, he interpreted these associations as twins of twins which he
466 called “cumulative twins”. In these twins, which look like single twins, the two individuals, A
467 and C, are oriented by hidden twins: **they** are due, for example, to an A-B twin, a B-C twin
468 and a special growth process which finally hides the B individual. This explanation for the
469 Emfola twin is currently accepted. We have tested the Carlsbad-Manebach cumulative twin (i.
470 e. the A-B twin is a Carlsbad twin and the B-C twin a Manebach twin). It gives rise to **an**
471 **intergrowth** with a good angle between the [001] directions but it clearly appears that the ($\bar{2}$
472 10) faces of the individuals I and II have not the same orientations as in our case (fig. 11c).

473 Nevertheless the angle of 52° is particular: it is very close to the supplementary angle
474 of the angle between the [001] directions found in the Manebach twin. Let us recall here that
475 one fundament of the twin theory (e.g. Friedel, 1904) states that if there is a *normal twin*

476 involving a crystallographic (*hkl*) plane, there is another twin (called a corresponding twin)
477 which is a *parallel twin* involving a crystallographic [*uvw*] axis. The orientation of the [*uvw*]
478 axis is close to the direction perpendicular to the (*hkl*) plane. Examples of corresponding
479 twins are not very frequent: the most quoted are the albite and pericline twins (Deer et al.,
480 **2013**). Let us consider now the Manebach twin which is a *normal twin* with the (001) plane.
481 The closest direction perpendicular to this plane is [205]. This direction is a candidate for the
482 axis of the corresponding *parallel twin* of the Manebach twin. The analysis of the
483 asymmetrical shapes of the ($\bar{2}01$) faces on the only one specimen associating two single
484 crystals (fig. 11) shows that the ($\bar{2}01$)_I and ($\bar{2}01$)_{II} faces of both individuals are deduced by a
485 rotation parallel to the composition plane and at least quasi parallel to the [205] direction.

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

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

495

496 4.10 Albite twin

497 The albite twin is a *normal twin* with the (010) plane. Mountain (1925) has detected it
498 on single crystals with a very rounded shape (the type I crystal following his classification).
499 This twin appears as thin lamellae that were detected with the microscope in thin sections. It
500 does not appear clearly on the shape of the crystals. Six crystals, with rounded and flat shapes
501 close to the description of the Mountain's type I crystals, exhibit smooth striae on the {110}
502 and/or { $\bar{1}10$ } faces and parallel to [001], which agrees with well-developed albite twins (fig.
503 12).

504

505 4.11 Single and near single intergrowths: rare or questionable to doubtful twins

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

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

519 - $[\bar{1}12]$ Nevada twin (Drugman, 1938): 2 specimens are in good agreement and 3
520 specimens are suspected (poor angular precision). **The twin lattice analysis gives a *non-***
521 ***Friedelian* twin; the indices, n , deduced from the 7 different perpendicular planes are in**
522 **between 6 and 15, with an obliquity, ω , between 5.71 and 1.22 respectively. With the**
523 **same software, this could be interpreted as a hybrid twin; then the effective twin index**
524 **n_E is 2.2.**

525 - $[\bar{4}30]$ twin (unnamed but quoted in Hintze, 1897): in a set of 12 specimens, some
526 **intergrowths seem to follow this law, some others with the close $[\bar{2}10]$ law and the last**
527 **specimens with axis close to the $[\bar{4}31]$ axis. Analysis gives indices, n , between 9 and 20**
528 **with obliquities, ω , between 5.8 and 3.2 respectively. These twins seem therefore highly**
529 **improbable. Consequently the reference to this twin law is more descriptive than confirmed.**

530 - $(\bar{1}\bar{1}2)$ or $(\bar{1}12)$ Goodsprings twins: Drugman (1938) has proposed this “twin” law as
531 descriptive: he did not confirm it, but noticed that a significant number of feldspar
532 intergrowths found in Goodsprings, Nevada, might be approximately described with this
533 “law”. We found 5 specimens that might be more or less described with this “descriptive twin
534 law”. **The twin lattice analysis confirmed that this twin is unlikely ($n=19$).**

535 - $(1\bar{1}1)$ Breithaupt twin (see Hintze 1897): 3 specimens approximately agree. **The**
536 **twin lattice analysis gives a *Friedelian* twin, with $n=3$ and $\omega=1.03$.**

537 - (130) (see Smith 1974): one specimen with a prismatic shape and a triangular section
538 agrees. **The twin lattice analysis gives a *Friedelian* twin, with $n=3$ and $\omega=2.50$.**

539 - (320) or $(3\bar{2}0)$ (mentioned by Gates, 1953, but not confirmed): one specimen well
540 agrees. **The twin lattice analysis recognized these twins are unlikely ($n=14$).**

541

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

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

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

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

552

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

556

557 **5. Conclusion**

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

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

573 The great number of twins also permits the relative abundance of the different kinds and
574 varieties of twins and their shapes **to be determined.** Our results show that the Erebus
575 anorthoclases give rise to a good estimation of the re-entrant corner effect. As far as we know,

576 there is no other example of such estimation, and the Erebus crystals and twins might be an
577 empirical support for future theoretical investigations about this effect.

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

582

583

584 **Acknowledgements**

585 The authors would like to acknowledge Alain Jeanne-Michaud for his great help for pictures
586 and photos. **We would like to thank the three reviewers for their useful comments and**
587 **corrections and especially reviewer 3 for his help and his analysis of the new twins using**
588 **the Geminography software.**

589

590

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

| | |
|--|---|
| <p>Single crystals or near single crystals : 8.1%</p> <ul style="list-style-type: none"> - Single crystal: 9 - Single crystal with small Carlsbad twin: 20 - Anomalous lenticular shape : 5 | <p>Manebach twins : 4%</p> <ul style="list-style-type: none"> Elongated: 7 Lenticular: 8 Broken: 2 |
| <p>Albite twins : 6 (1.4%)</p> | <p>Carlsbad-B twins: 21.4%</p> <ul style="list-style-type: none"> Simple “arrow head” Carlsbad B twin: 6 Asymmetrical Carlsbad twin: 78 Y shaped Carlsbad twin: 6 |
| <p>X shaped Carlsbad-B twins: 100 (23.8%)</p> | <p>G or Cunnersdorf twins: 4.8%</p> <ul style="list-style-type: none"> - Carlsbad-Carlsbad twin: 6 - Single crystals: 7 - Lamellar part: 7 |
| <p>Tazieff twins: 2.1%</p> <ul style="list-style-type: none"> - Carlsbad-Carlsbad twin: 6 - Single crystal-Carlsbad twin: 3 | <p>Erebus twin: 3.1%</p> <ul style="list-style-type: none"> - Carlsbad-Carlsbad twins: 8 - Single crystal-Carlsbad twin: 5 |
| <p>Baveno twins: 6.2%</p> <ul style="list-style-type: none"> - Carlsbad-Carlsbad twin: 24 - Single crystal-Carlsbad twin: 2 | <p>Prism twins: 5%</p> <ul style="list-style-type: none"> - Carlsbad-Carlsbad twin: 15 - Single crystal-Carlsbad twin: 3 - With other twins: 3 |
| <p>Rare, suspected or doubtful twins: 30 (7.1%)</p> | <p>Other single intergrowths: 18 (4.3%)</p> |
| <p>Confused and indistinct intergrowths: 18 (4.3%)</p> | <p>Broken indistinct parts: 18 (4.3%)</p> |

766

767

768 **Table 2: Statistics on the size of Erebus volcano single crystals and Carlsbad B twins.**

769 W, T and L are measured in millimeters (the number of specimens is lower than the number
770 of specimens reported in table 1 because some of them are broken, **the ranges of length are**
771 **indicated between the square brackets and the standard deviation σ_{n-1} in parenthesis).**

772

| | 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 [11-30] (5.4) | 11.7 [8.1-15.5] (2.3) | 43.3 [18-60] (9.8) | 1.85 (0,25) | 2.02 | 1.19 |
| Asymmetrical Carlsbad twin 36 specimens | 21.4 [11-32] (6.5) | 11.11 [7.4-16.8] (3.0) | 45 [20-65] (11.8) | 2.11 (0,4) | 1.93 | 1.07 |
| X-shaped Carlsbad twin 40 specimens | 19.8 [8-32] (5,6) | 10.1 [4-14.7] (2,4) | 51 [27-75] (11.8) | 2.62 (0,4) | 1.92 | 1.02 |

773

774

775 **Figure captions***

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

778

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

781

782 Figure 2: (a) X shaped Carlsbad **B** twin, the previously called X Carlsbad B twin (#13529,
783 68.9 x 24.4 x 13.6 mm), (b) sketch.

784

785 Figure 3: Symmetrical Carlsbad B single twin, (a) photo, (b) sketch (#13533, 31.5 x 12.9 x
786 7.0 mm).

787

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

791

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

794

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

796

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

799

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

802

803 Figure 9: Cunnersdorf twin, (a) sketch, (b) single crystal-single crystal (#13539, 24.9 x 14.3 x
804 14.3 mm), (c) Carlsbad-Carlsbad (#13540, 40.4 x 21.6 x 27.5 mm), (d) **the right end with**
805 **one face is due to a flattened individual in Cunnersdorf twin orientation.**
806 (#13541, 43.4 x 19.3 x 11.6 mm).

807

808 Figure 10: The newly described Erebus twin, (a) photo (here single crystals, #13545, 47.5 x
809 23.4 x 24.8 mm), (b) sketch.

810 .

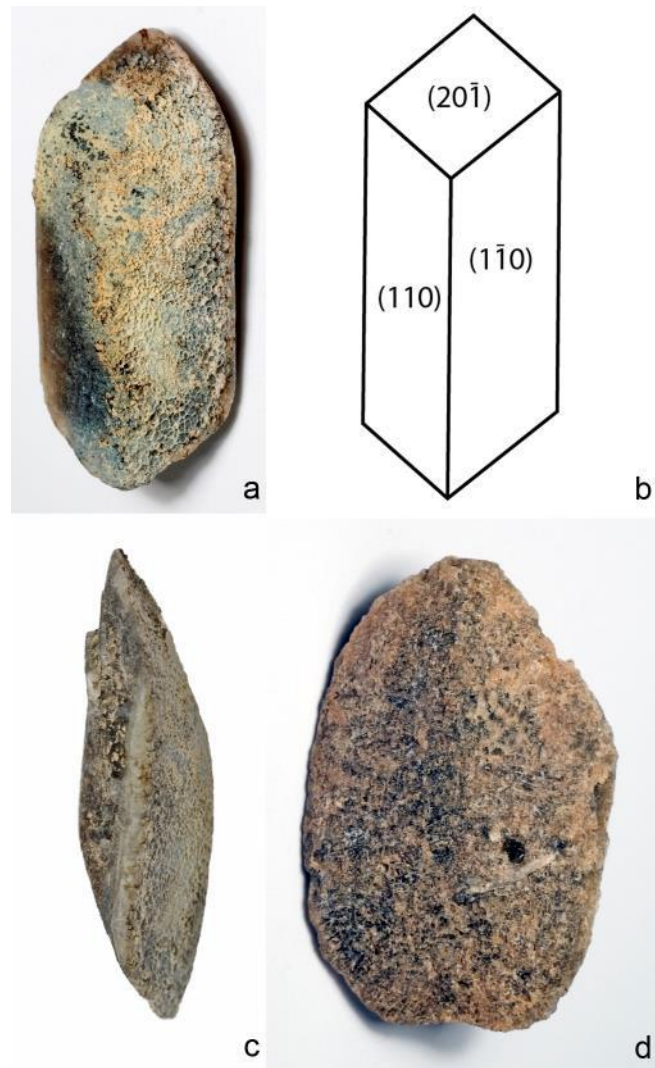
811

812 Figure 11: The newly described Tazieff twin, (a) photo (#13542, 24.3 x 14.5 x 14.1 mm), (b)
813 sketch and, (c) theoretical sketch of the cumulative Carlsbad-Manebach twin, here the 1 and
814 3 individuals (the $(\bar{2}10)$ faces of the 1 and 3 individuals do not have the same orientations as
815 in (b)).

816

817 Figure 12: **This rounded shaped crystal is attributed to an albite twin (Mountain, 1925)**
818 (#13532, 35.6 x 33.3 x 10.9 mm).

819

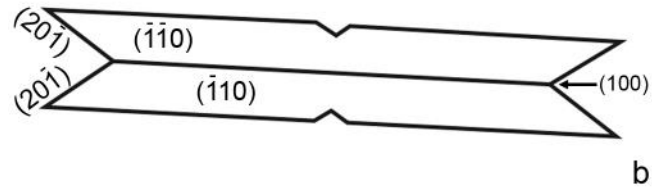


821

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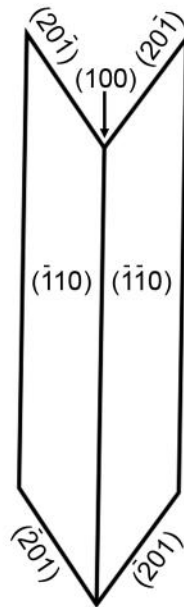
824



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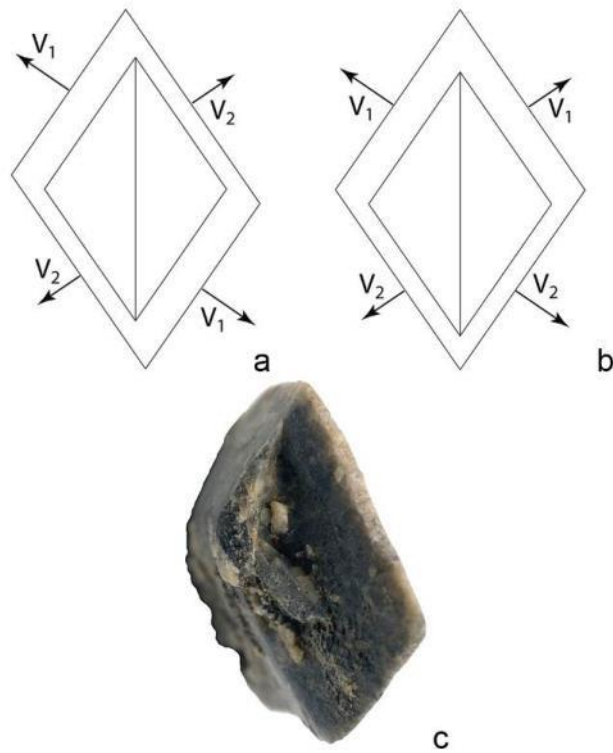
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829

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832



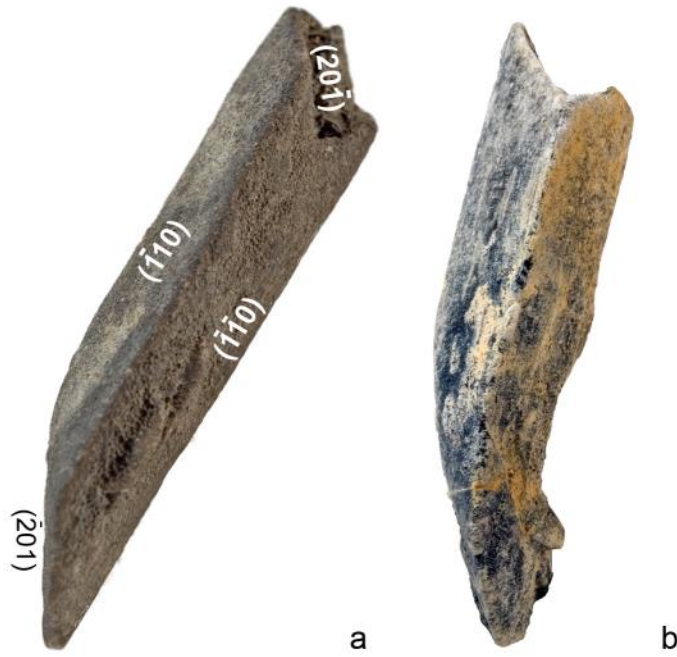
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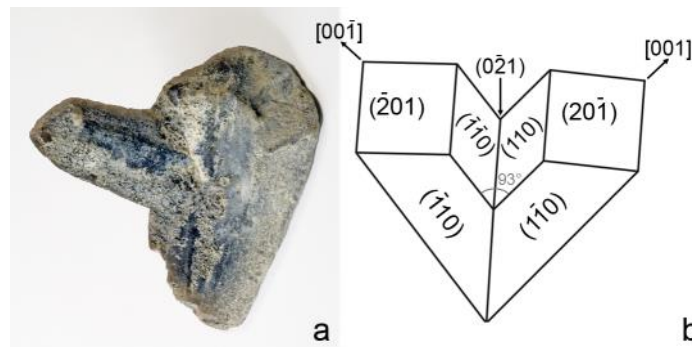
837



838

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841



842

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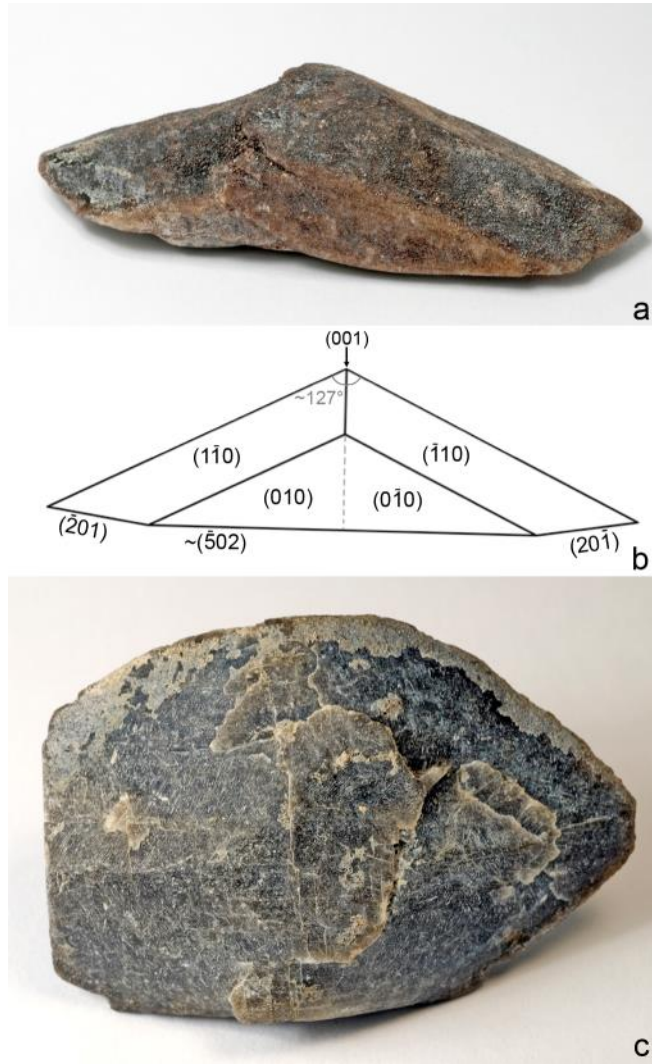
844



845

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848

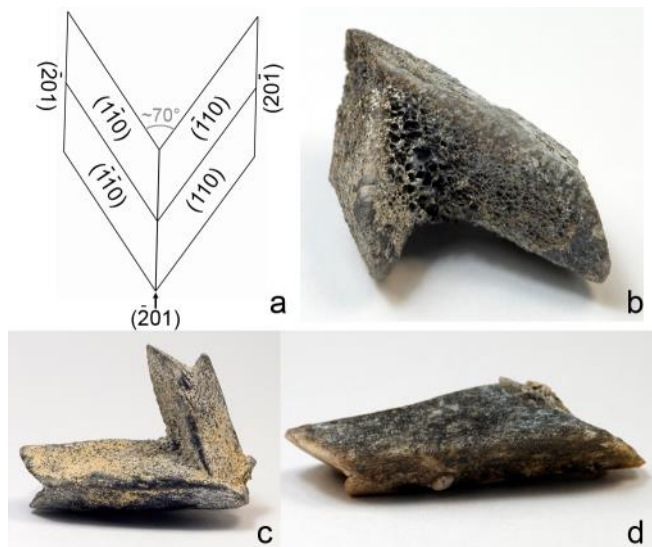


849

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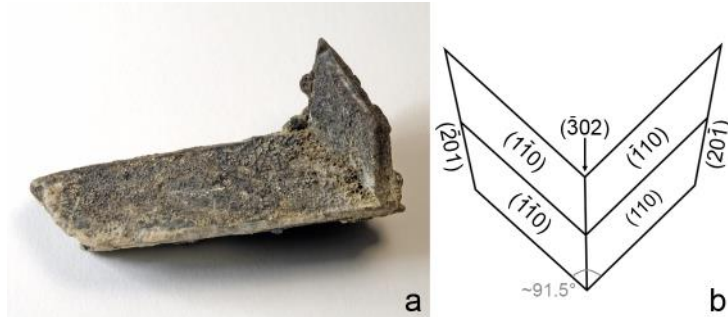
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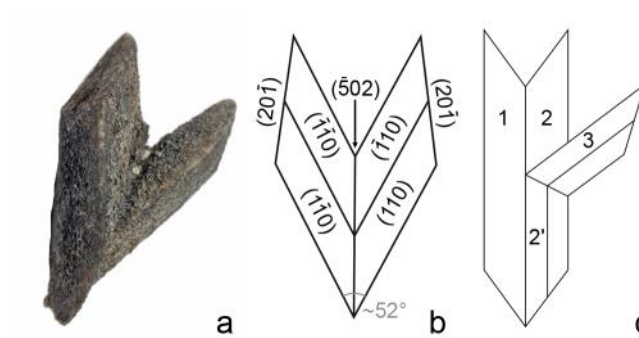


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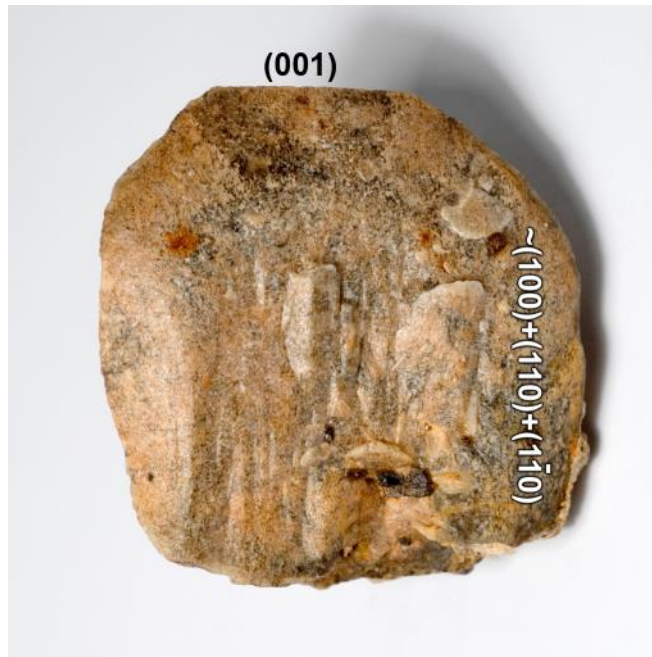
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 863



864
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 869



870

871 **Figure 12: This rounded shaped crystal is attributed to an albite twin (Mountain, 1925)**

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873

874